Modelling the impact of the Burdekin, Herbert, Tully and Johnstone River plumes on the Central Great Barrier Reef

Brian King[1], Felicity McAllister[2], Terry Done[2]

[1]Asia-Pacific Applied Science Associates
[2]Australian Institute of Marine Science

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[1]Asia-Pacific Applied Science Associates
PO Box 1679, Surfers Paradise Qld 4217 Australia. Phone 61-7-5574 1112
[2]Australian Institute of Marine Science
PMB #3 Townsville MC, Townsville Qld 4810, Australia. Phone: +61-7-4753 4444

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CRC Reef Research Centre Ltd
PO Box 772
Townsville Queensland 4810 Australia
Website: www.reef.crc.org.au
Ph: +61 7 4729 8400
Fax: +61 7 4729 8499

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INTRODUCTION

As part of the water cycle, rivers drain freshwater runoff from rainfall events over land. The runoff collects a variety of substances as it moves through the river's catchment-lands and waterways including nutrients, sediments and contaminants depending on the catchment characteristics and land-use practices. Upon reaching the sea at the river's mouth, the runoff drives a buoyant plume into coastal and shelf waters. The plume eventually spreads and mixes and moves around with the winds and currents. This mixing with ambient coastal waters will ultimately dilute the runoff plume as well as any concentrations of sediments, nutrients and contaminants carried within the plume.

In the wet and dry tropical catchments adjoining the Great Barrier Reef (GBR), river discharges are highly seasonal and usually event-driven in nature and result from rainfall events associated with evolving monsoon troughs or passing tropical cyclones (Furnas and Mitchell 2000; Wolanski, 1994). Also, the unpredictable nature of rainfall and runoff events, and the unsteadiness and patchiness of the resulting plume intrusions in a complex region such as the GBR, has traditionally made data logistically difficult to collect. Further, direct rainfall inputs onto the shelf-waters can also lower surface salinity significantly (Wolanski, 1994) and at a time when river discharges are also significant. Thus large spatial mapping of salinities was needed to determine the origins of lower salinity events (< 34 ppt) within the reef matrix of the GBR.

Historically, significant plume intrusions into the GBR have been observed. Data presented in the literature (Wolanski *et al.*, 1997; Ayukai *et al.*, 1997; Wolanski, 1994; O'Neill *et al.*, 1992; Wolanski and Ruddick, 1981) report measurements of reduced salinities associated with particular events. Wolanski and Van Senden (1983) reported the most detailed survey todate, which covered the 1981 flood events from the Burdekin, Herbert, Tully, Johnstone and Barron Rivers. These studies have also provided some insight into the dynamics influencing the fate of river plumes in the GBR. However, understanding all the possible fates of river plumes under a variety of climatic conditions is needed for the management of the GBR because of their ability to transport pollutants from human activities on land into the GBR Marine Park. Hence, information on the fate of plumes over daily to decadal time scales is ultimately required to comprehensively determine the full range of impacts from river plumes in the GBR.

The aim of this current project was to utilise these historical observations to calibrate a 3-dimensional hydrodynamic plume model of the Burdekin, Herbert, Tully, and Johnstone Rivers in flood (see location map in figure 1). The model's predictions have been verified against field observation where possible (See also King *et al.*, 1998). The model was used to produce a comprehensive long-term time varying and 3-dimensional spatially varying database of the fate and mixing of plume waters from the Burdekin, Herbert, Tully and South Johnstone Rivers from 1973-1998 (McAllister *et al.*, 2000).

GEOGRAPHIC SETTING

The rainfall catchment area adjoining and impacting the GBR Marine Park totals 424,000 km^2 and consists of over 35 significant drainage basins. Of these, the Burdekin River has the second largest catchment area, about 130,000 km^2, equivalent to the land area of Greece. Although the Fitzroy basin is slightly larger, the Burdekin River has the largest recorded mean annual flow (approximately 9,700,000,000 m^3 per year) for any river adjacent to the world heritage listed Great Barrier Reef (Wolanski 1994). The median annual flow is significantly lower at approximately 5,300,000,000 m^3 per year.

The river mouth is located between Cape Upstart to the south and Cape Bowling Green to the north (Figure 1). The run-off, while extensive, is also highly variable, limited to the occasional flood event (0-3 per year) usually occurring during the Austral summer months of December to March.

The catchment areas further north of the Burdekin lie within more rugged and mountainous terrain resulting in more river systems transversing the region draining significantly smaller catchments. The major river systems here are the Herbert, Tully and Johnstone Rivers (Figure 1).

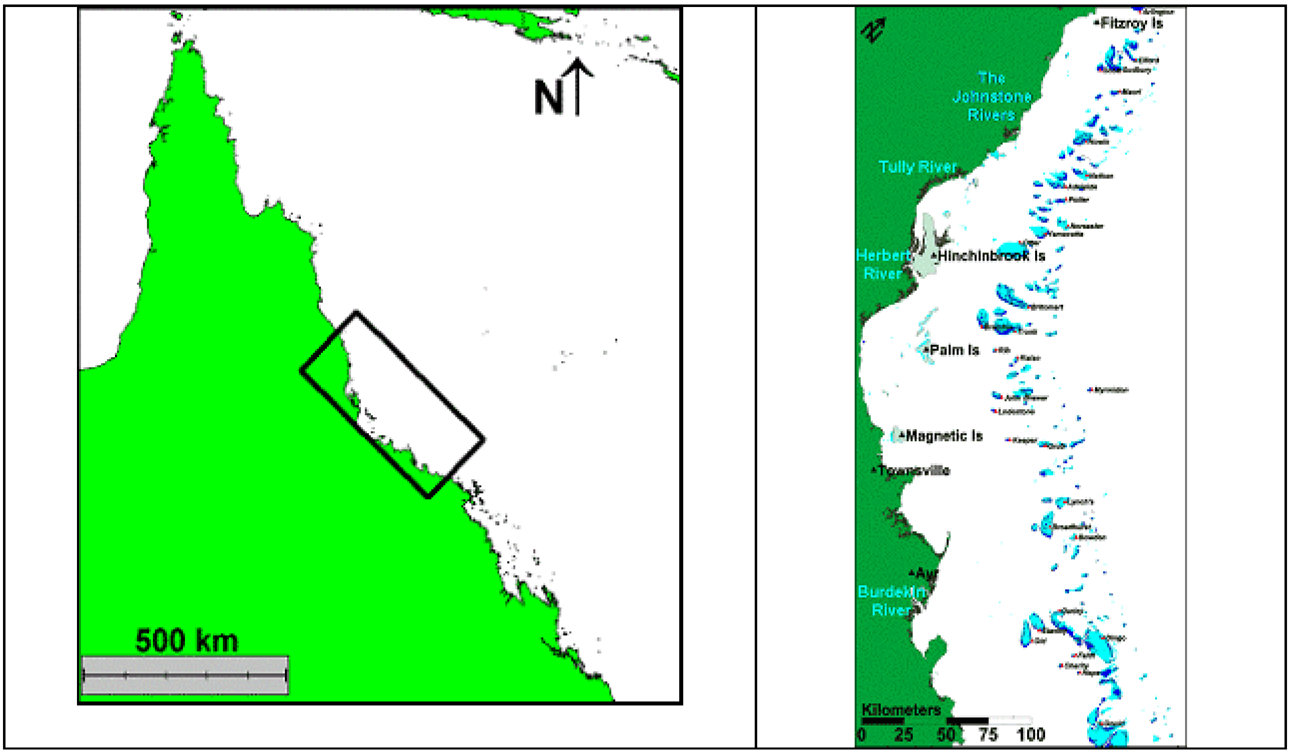


Figure 1. Map of the Burdekin, Herbert, Tully and Johnstone River along the Queensland coastline. Green colours depict land, continental islands and coastal mangrove swamps. Blue colours show the individual reef flats and lagoons of the Central Great Barrier Reef.

RIVER DISCHARGE CHARACTERISTICS

Daily discharge data from the Burdekin River (1951-1998) was obtained from the Queensland Water Resources Commission. The data, since 1951, demonstrates the decadal, annual and inter-annual temporal variability associated with runoff events in the Central GBR region. From the daily discharge data measured in the Burdekin River, the peak flow for the year was determined and ranked from largest to smallest (see Table 1). The daily discharge data was also summed to give a total volume discharged for each water year (July – June) and then ranked from largest to smallest values (see Table 1). From the ranking, return periods based on the total volume of freshwater discharged by the Burdekin River over the last 47 years were estimated using a Pearson III Type Distribution (ARA, 1998) and are given in Table 2. From Table 2, it can be seen that the wet season of 1973-1974 was an unusually large event. Such an event of this magnitude is estimated to have a likely return period of once every 79 years.

The decadal variability in the discharge behaviour of the Burdekin can also be seen in Table 2, since almost all of the big discharge years, which occurred during the last four decades, either happened during the 1950s, or 1970s. Table 2 shows that there were a considerable number of years when discharge from the river was negligible, such as 1994-1995, 1992-1993, 1991-1992, 1986-1987, 1984-1985, and 1981-1982.

A significant dam was built across the Burdekin River and was completed just prior to the significant rainfall event of the 1990-1991 wet-season. The dam was quickly filled by this event, as its total capacity is approximately 2 billion tonnes of water (2,000,000 megalitres), i.e. only 5% of the total water volume that discharged that year. Further, a return period analysis was conducted on the Burdekin's annual discharge data from both pre and post dam years. No significant variation in the behaviour of the discharge data analysed was evident as a result of the construction of the Burdekin Dam.

Daily discharge data for the Herbert, Tully and North and South Johnstone rivers was also obtained from the Queensland Water Resources Commission. This data was also summed to give a total volume discharged for each water year (July – June). Discharge data from the South Johnstone River and the North Johnstone River were combined to produce one outfall. Stream gauging data for the Tully River were unavailable prior to the 1972-1973 wet season.

Figure 2 illustrates that the Burdekin River's annual discharge volumes almost always exceed those of the Herbert, Tully and Johnstone Rivers, primarily as a result of the Burdekin's significantly larger catchment size. Two obvious exceptions occurred in 1977 and 1986 due to the movements of tropical cyclones over the region (Puotinen *et al.*, 1997), highlighting the spatial variability associated with these extreme meso-scale storm events.

Table 1. Discharge characteristics (maximum flow rate and total discharge volume) for the Burdekin River from 1966-1995 ranked (decreasing magnitude) from the most significant events to the least significant events.

Rank	Maximum Flow Rate		Total Discharge	
	Year	(m^3/s)	Year	(ML)
1	1974	25,472	1974	53,878,655
2	1968	23,931	1991	40,411,687
3	1972	22,629	1972	18,897,175
4	1991	19,665	1981	17,967,853
5	1978	13,199	1968	16,095,218
6	1979	11,700	1979	15,590,866
7	1989	10,935	1976	11,828,423
8	1981	10,684	1990	9,529,963
9	1970	10,523	1989	9,056,236
10	1983	10,031	1983	8,758,709
11	1988	9,058	1977	8,565,482
12	1980	7,672	1975	8,482,719
13	1975	6,545	1971	6,136,544
14	1977	6,482	1984	5,287,534
15	1976	5,648	1978	5,170,492
16	1990	4,562	1970	4,856,183
17	1971	4,382	1980	4,675,890
18	1986	4,114	1986	3,801,182
19	1984	3,508	1988	3,791,881
20	1973	3,054	1973	3,603,037
21	1966	2,467	1994	2,906,115
22	1994	2,446	1967	2,404,477
23	1967	2,167	1982	2,330,380
24	1982	793	1966	2,204,311
25	1985	647	1985	1,352,955
26	1993	412	1995	794,576
27	1995	267	1987	579,662
28	1987	248	1993	561,551
29	1969	194	1992	509,291
30	1992	61	1969	351,184

Table 2. Return periods and Annual Exceedence Probabilities (AEP %) calculated for the total volume of freshwater discharged by the Burdekin River from 1951-1998.

Rank	Water Year	Discharge (Megalitres)	A.E.P. (%)	Return Period
1	1973-1974	53,878,655	1.27	78.7
2	1990-1991	40,411,687	3.39	29.5
3	1957-1958	28,068,886	5.51	18.2
4	1954-1955	24,146,521	7.63	13.1
5	1955-1956	22,105,966	9.75	10.3
6	1953-1954	21,018,573	11.86	8.4
7	1971-1972	18,897,175	13.98	7.2
8	1980-1981	17,967,853	16.10	6.2
9	1967-1968	16,095,218	18.22	5.5
10	1978-1979	15,590,866	20.34	4.9
11	1975-1976	11,828,423	22.46	4.5
12	1952-1953	10,968,693	24.58	4.1
13	1956-1957	9,859,008	26.69	3.7
14	1962-1963	9,690,007	28.81	3.5
15	1989-1990	9,529,963	30.93	3.2
16	1988-1989	9,056,236	33.05	3.0
17	1982-1983	8,758,709	35.17	2.8
18	1996-1997	8,703,774	37.29	2.7
19	1976-1977	8,565,482	39.41	2.5
20	1974-1975	8,482,719	41.53	2.4
21	1997-1998	8,047,517	43.64	2.3
22	1970-1971	6,136,544	45.76	2.2
23	1958-1959	6,002,438	47.88	2.1
24	1983-1984	5,287,534	50.00	2.0
25	1977-1978	5,170,492	52.12	1.9
26	1959-1960	5,026,967	54.24	1.8
27	1969-1970	4,856,183	56.36	1.8
28	1979-1980	4,675,890	58.47	1.7
29	1985-1986	3,801,182	60.59	1.7
30	1987-1988	3,791,881	62.71	1.6
31	1964-1965	3,747,057	64.83	1.5
32	1972-1973	3,603,037	66.95	1.5
33	1993-1994	2,906,115	69.07	1.4
34	1961-1962	2,623,611	71.19	1.4
35	1966-1967	2,404,477	73.31	1.4
36	1981-1982	2,330,380	75.42	1.3
37	1965-1966	2,204,311	77.54	1.3
38	1995-1996	1,847,753	79.66	1.3
39	1963-1964	1,787,876	81.78	1.2
40	1984-1985	1,352,955	83.90	1.2
41	1960-1961	1,341,715	86.02	1.2
42	1951-1952	931,768	88.14	1.1
43	1994-1995	794,576	90.25	1.1
44	1986-1987	579,662	92.37	1.1
45	1992-1993	561,551	94.49	1.1
46	1991-1992	509,291	96.61	1.0
47	1968-1969	351,184	98.73	1.0

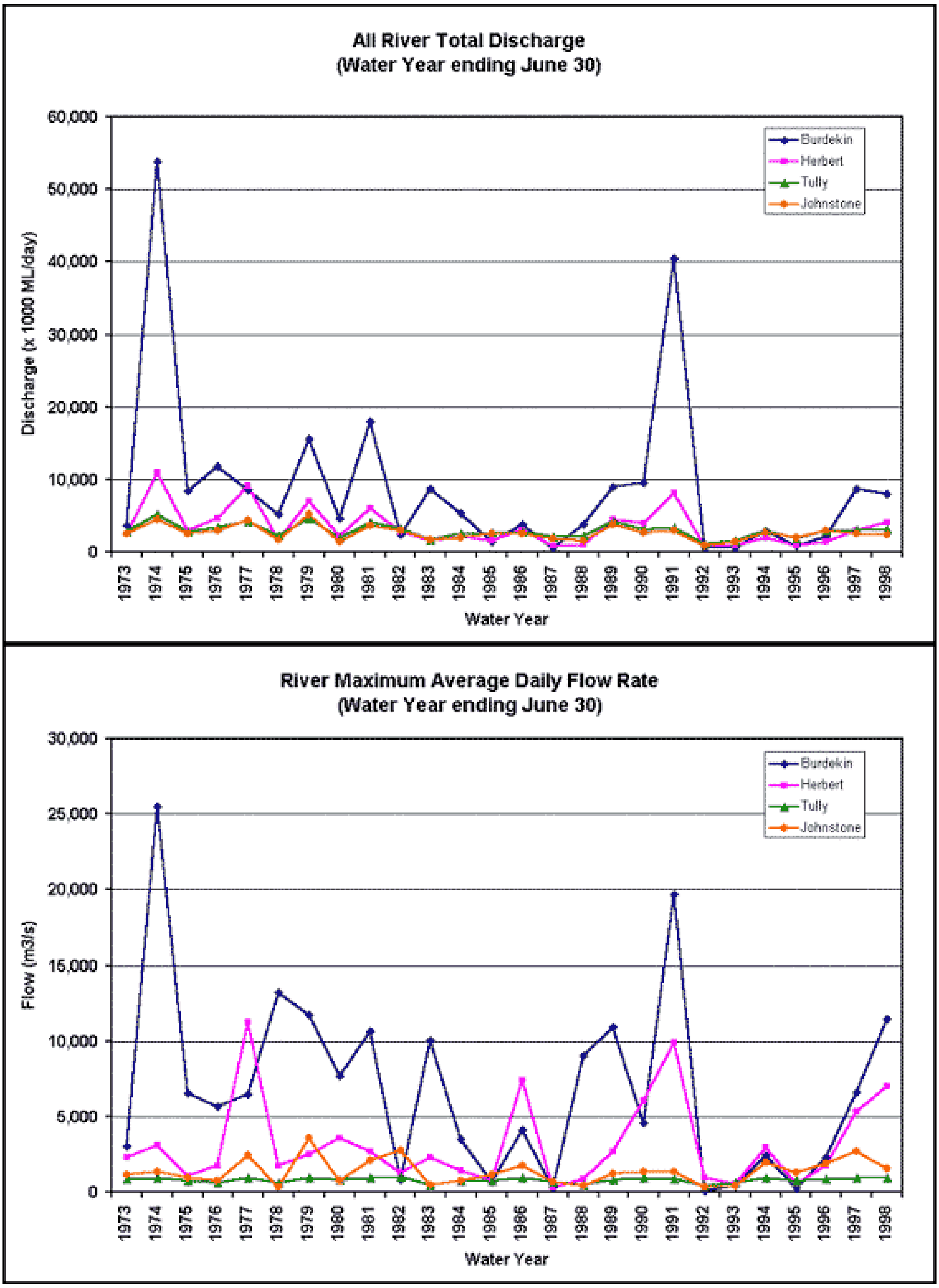
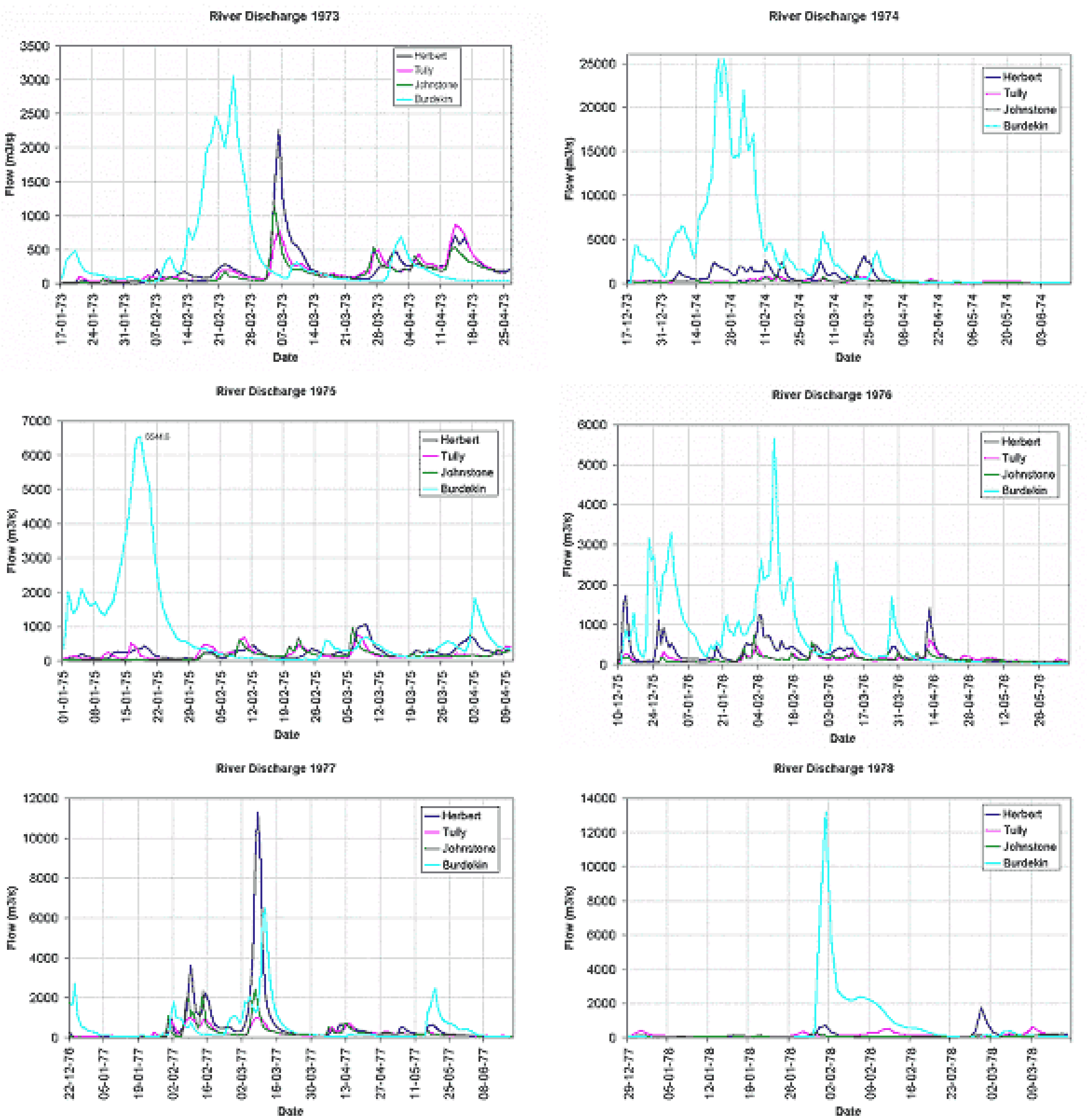
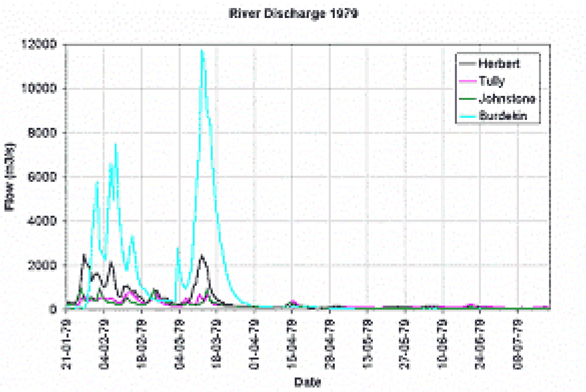


Figure 2. Time-series plot of total volume of freshwater discharged by the Burdekin, Herbert, Tully and Johnstone Rivers for each water years 1972/1973 – 1997/1998.

Figure 3 shows the daily discharge hydrographs (flow rates) for the Burdekin, Herbert, Tully and Johnstone Rivers for the wet seasons between 1072-1973 and 1997-1998 demonstrating the spatial and temporal variability inherent in the flow rates from the major rivers of the Central GBR. Note that the rainfall event most influencing the 1986 hydrographs was due to the passage of Cyclone Winifred over all catchments (Puotinen *et al.*, 1997). Figure 3 also shows three significant rainfall events occurred in 1981. The first two events resulted from the presence of the monsoon trough over all catchments, while the last event was associated with tropical cyclone Freda.

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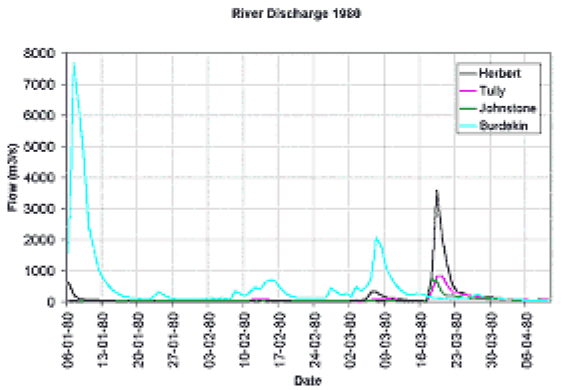
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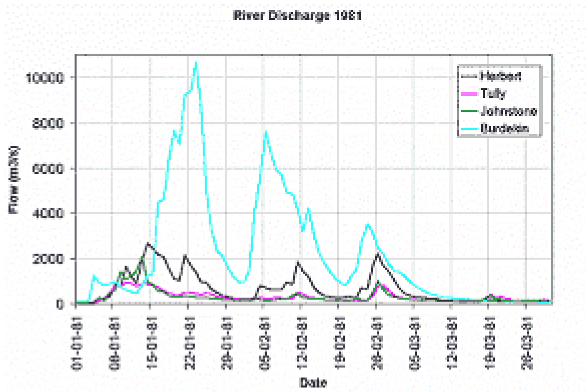
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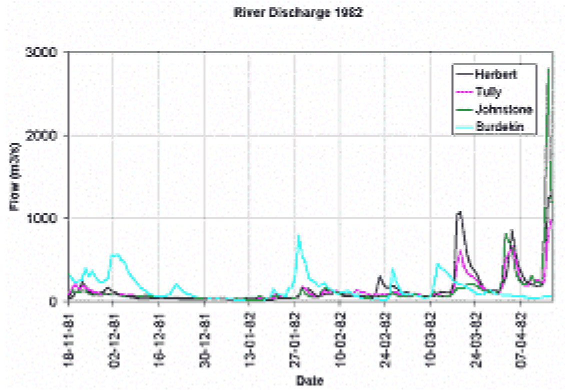
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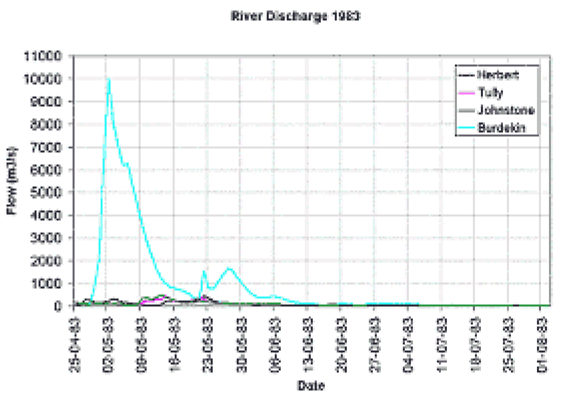
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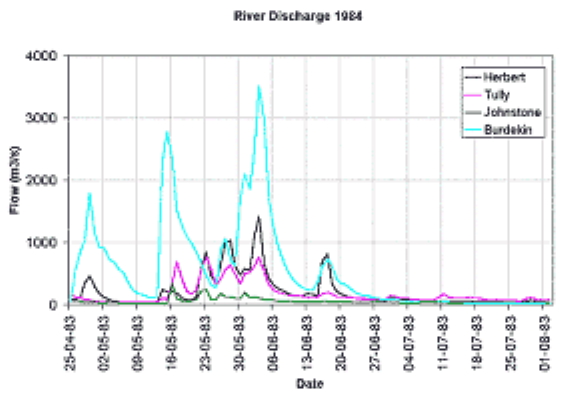
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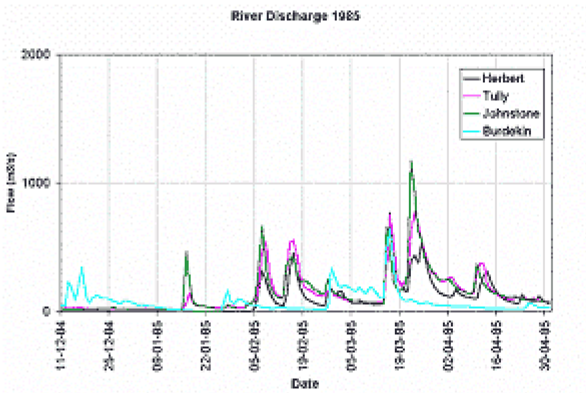
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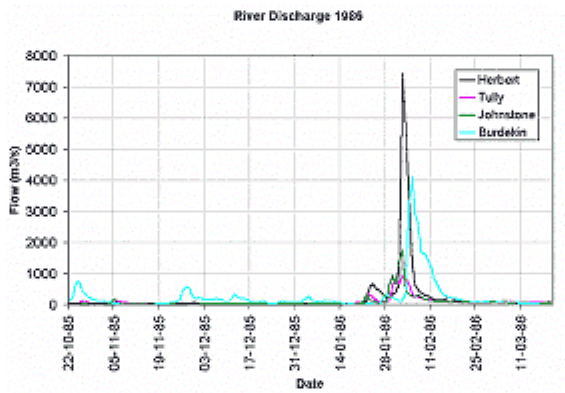
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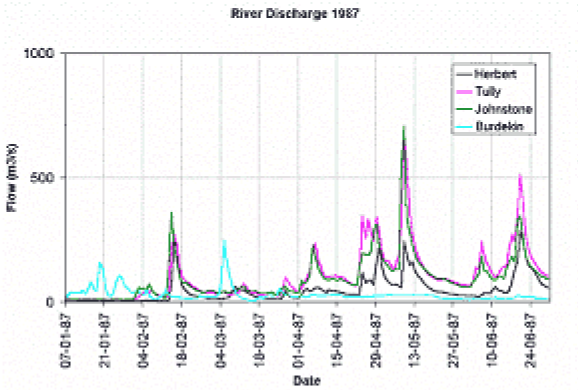
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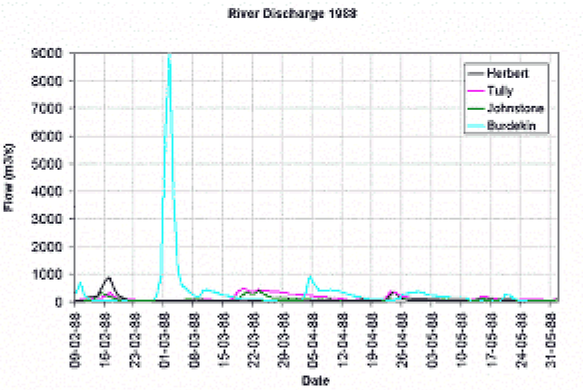
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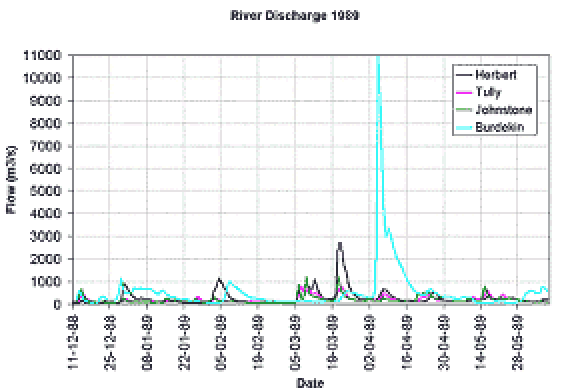
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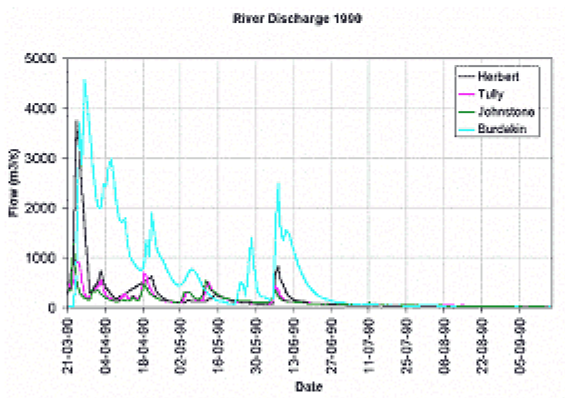
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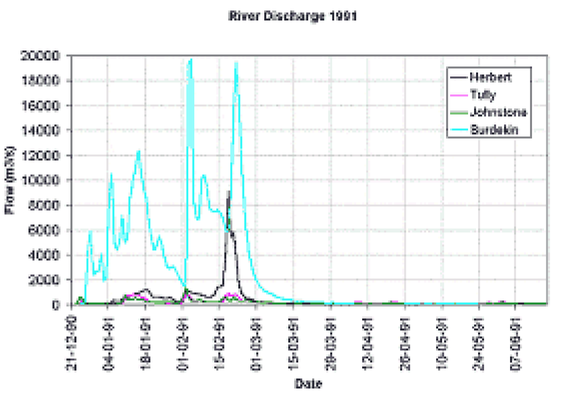
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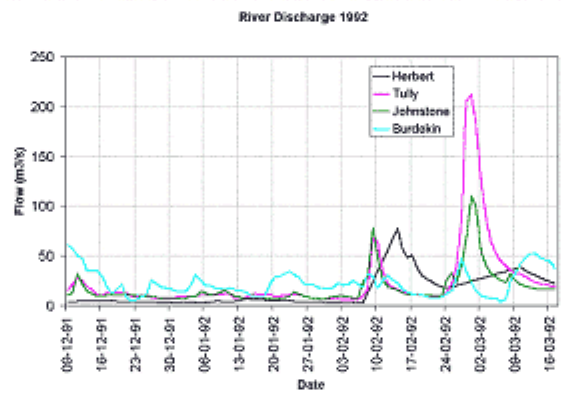
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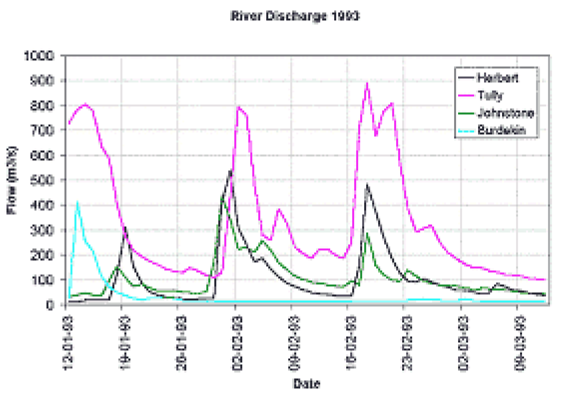
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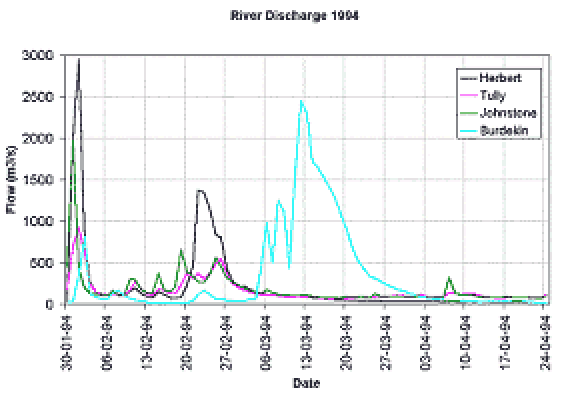
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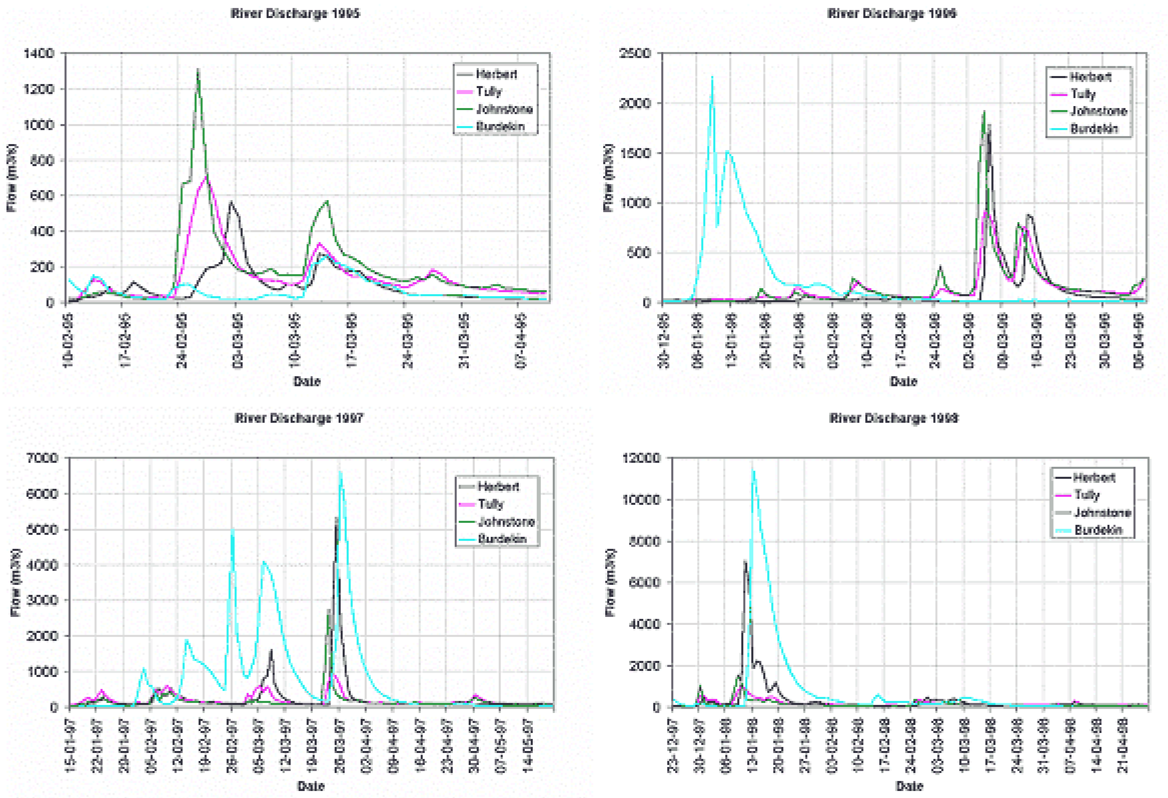


Figure 3. The discharge hydrographs (flow rates) for the Burdekin, Herbert, Tully and Johnstone Rivers for the wet seasons between 1973 and 1998 showing the spatial and temporal variability in the flow rates from the major rivers of the Central GBR.

MODELLING RIVER PLUMES IN THE CENTRAL GBR.

The MECCA 3-dimensional hydrodynamic model (see Hess, 1989) from NOAA, which incorporated river plume dynamics into the model's governing 3-dimensional equations was used for this study. The model was designed to predict tidal, wind and density driven flows in bays and on continental shelves. MECCA has been extensively applied to study the salinity and temperature distribution in Chesapeake Bay and surrounding shelf areas (Hess 1986).

King *et al.* (1998) calibrated and verified a 3-dimensional hydrodynamic model of the Burdekin River in flood. The model was used to produce a comprehensive long-term time varying and 3-dimensional spatially varying database of the fate and mixing of plume waters from the Burdekin, Herbert, Tully and South Johnstone Rivers (McAllister *et al* 2000).

The MECCA model uses a 3-dimensional grid to mathematically represent elements of the water column within the study region. King *et al.* (1998) designed a grid that covered the entire shelf of the central section of the GBR from Cairns to Bowen (Figure 4). The numerical grid representing the domain had over 100,000 computational points, that is, 5 layers in the vertical, 211 points in the along-shelf direction and 95 in the across-shelf direction. The grid elements spacing in the horizontal plane were 2 km x 2 km throughout, while the vertical grid spacing varied according to the depth (sigma representation). For example, depths near the coast were of the order of 5 - 10 m, thus the vertical grid spacing would be 1 - 2 m respectively. While current computer hardware limitations prevent the use of a finer grid at this stage, the 2 km resolution of the bathymetry is sufficient to represent the individual reefs of the GBR in this region as shown in Figure 4.

The model was initially set up to simulate a flood of freshwater from the Burdekin River into the coastal waters of the Great Barrier Reef (GBR). King *et al.* (1998) verified this model for the entire 1981 flood event. This was achieved by forcing the model to incorporate the daily variability in the river's discharge and actual wind data (at 3 hourly intervals), against the historical field salinities reported in Wolanski and Van Senden (1983). Comparisons between model results and field data for 3 different days of field surveys shows very good agreement between the observed and predicted salinity distribution in coastal waters at corresponding times. King *et al.* (1998) also undertook sensitivity analysis on the 1981 model simulations. The model showed that the main driving influences on the fate of the Burdekin River plume water were the discharge volume of the river (in the near field, that is, less than 100 km from the mouth) and the local wind forcing in the far field. Thus each year, one would expect different plume trajectories depending on the time-varying nature of both the wind and the rainfall.

The time-step of the model was set to simulate the river dynamics at 30 second intervals. Such high temporal resolution was required to ensure the correct representation of the buoyancy terms, since discharge rates from the Burdekin can exceed 25,000 m^3/s at times.

Wind data (at 3 hour intervals) was obtained from either the nearby Mackay weather station or from the nearby AIMS weather station. Daily discharge data for the Burdekin, Herbert, Tully and South and north Johnstone Rivers was obtained from the Queensland Water Resources Commission. Discharge data from the South Johnstone River and the North Johnstone River were combined to produce one outfall. Stream gauging data for the Tully River were unavailable prior to the 1972-1973 wet season. Given these restrictions on discharge and wind data availability, the simulations for the Burdekin River in flood were conducted from the 30 years period 1966-1995. The simulations of the combined Burdekin, Herbert, Tully and Johnstone Rivers in flood were conducted for the 26-year period, 1973-1998.

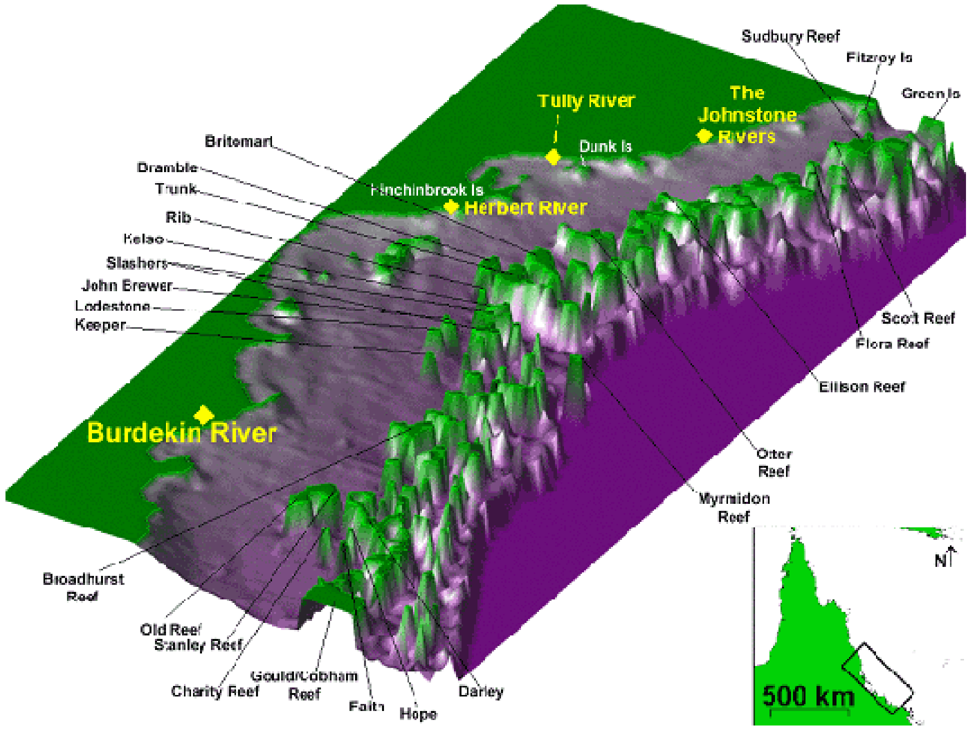


Figure 4. Model depth grid at 2 km x 2 km resolution representing the Burdekin, Herbert, Tully and Johnstone Rivers and adjacent coastline and a 3-dimensional rendered view of the shelf bathymetry and reef matrix of the Central Great Barrier Reef.

To determine dilution ratios from the model, the initial ambient salinity levels were set to background levels throughout the model. Ambient salinity levels in the GBR are known to fluctuate due to a number of processes such as offshore oceanic upwelling events and direct rainfall. Wolanski, (1994) shows that 35 ppt is typical for waters in the GBR and hence, 35 ppt was defined within the model as the background salinity. Hence, the model calculated the mixing of freshwater runoff with ambient coastal water. The amount of salt contained in any resulting mixture of runoff and ambient waters defines the salinity for each and every cell in the model. Since, the only source of freshwater in the model is introduced as runoff, the salinity levels in the model give a direct measure of how much runoff water has diluted with non-runoff water (set at 35 ppt). For example, a salinity of 0 ppt is all freshwater, a salinity of 17.5 ppt is an even mix of freshwater and sea water, a 31.5 ppt means a 10% content of freshwater present, a 33.5 ppt contains less than 5% freshwater. Regions of 35 ppt within the model domain contain no freshwater.

The model's predicted distribution of surface salinity was recorded at 6 hourly intervals for all 26 years of simulated floods. Since there are 95 x 211 grid cells in each layer in the model domain, the combined database contained the spatially-varying and time-varying salinity distributions at over 20,000 points every 6 hours for a 26 year period.

It is worth noting that to produce such a dataset was a significant computational effort requiring in excess of 10 quadrillion calculations to produce from a dedicated PIII 500 MHz PC.

EXAMPLES FROM THE FLOOD SIMULATIONS

The discharge data for 1981 (Figure 3) shows that three separate flood events occurred during this wet-season. The total volume of freshwater discharged into the GBR from the Burdekin River catchment area at this time was a massive 18 billion tonnes (or 18 km^3) of water. Table 1 shows that this volume corresponds to an event that has an expected annual return period of every 6.2 years. King *et al.* (1998) simulated the entire 1981 flood event period from 1 January, 1981 until 31 March, 1981. Figures 5 - 8 show snapshots of surface salinity from the model simulations of the 1981 flood event for the Burdekin, Herbert, Tully and Johnstone Rivers. These figures demonstrate that the regions of impact from each individual river overlaps at times. Further, it can be seen that the movement of the plumes from the smaller rivers are very dependant on the wind forcing and frequently flow southward with the wind while the Burdekin's near field flow is almost always northward due to the Coriolis Force.

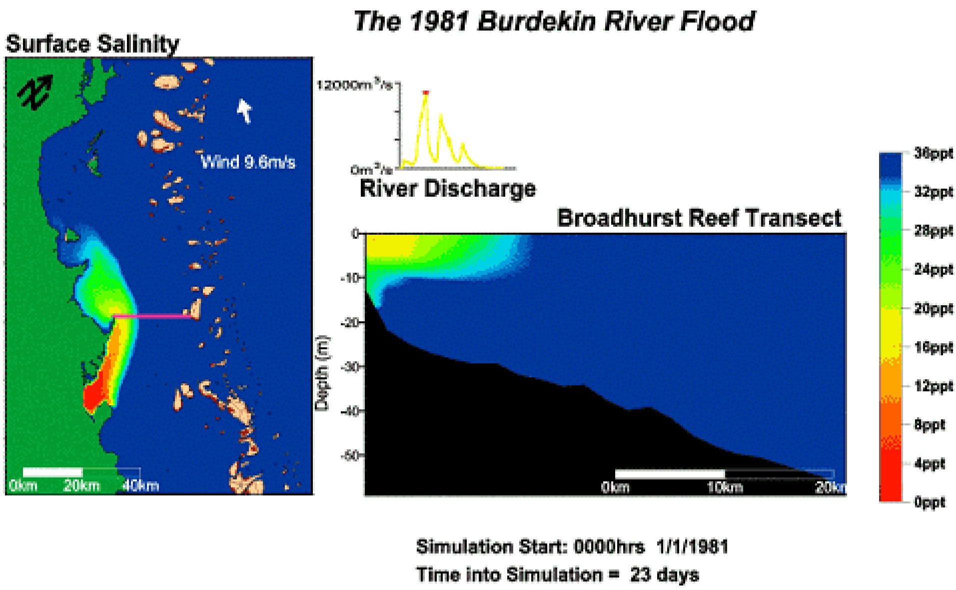


Figure 5. The figure shows the surface salinity distribution and vertical salinity profile map at the peak of the first flood event for 1981.

On Day 23 (24 January 1981), the Burdekin River reached the peak discharge of this flood at 12,000 tonnes of runoff per second (Figure 6). The left screen shows the surface salinity distribution over the whole model domain. The right screen depicts a vertical slice through the river plume along a transect from Cape Bowling Green to Broadhurst Reef demonstrating its 3D structure in this region. The insert graph shows the discharge rates over the 1981 wet season (m^3/s) starting from January 1, 1981 and the red asterisk indicates the flow rate for each snapshot. The wind vector represents the wind speed and direction at each time. The wind vector at this time showed that the wind was strong and from the SE at 10 ms^{-1} or about 20 knots. As a result of both these conditions, freshwater filled the entire Upstart Bay and a tongue of the brackish water (<30 ppt) stretched 150 km northward along the coast to reach Magnetic Island. This extensive excursion by plume waters is driven both by the SE winds and the massive strength of the river's discharge, which turns left at the mouth, a result of the effects of the Coriolis Force in the Southern hemisphere (that is, due to the Earth's rotational effects) and flows northward along the coast.

Due to the heavy rainfall flooding also occurred in the Herbert, Tully and to a lesser extent in the Johnstone rivers as shown in figure 6. Due to the topography of the coastline and the strong SE the resulting river plumes were pushed hard against the coastline producing thin river plumes extending both Northward and Southward along the coastline.

The plumes often touch the bottom in the shallow coastal regions (< 10-15 m depending on wind and discharge rate). As it spreads offshore, its freshwater content will most likely make it more buoyant than deeper offshore waters (Figure 5). This buoyancy difference further drives movement of the plume. This buoyancy–driven, across-shelf current will be a function on the density gradients across the shelf at the time. Hence the plume floats and generates a stratified water column in the deeper coastal waters along the marked transect. At the end of the first and major discharge event, the SE winds weakened at this time, though had advected the plume and the 30 ppt contour from the Burdekin almost 200 km from the mouth of the river to surround the continental islands of Cleveland Bay and Halifax Bay (see Figure 6). The river plume produced by the Herbert, Tully and Johnstone rivers extended 200 km from just south of the Herbert to Green Island.

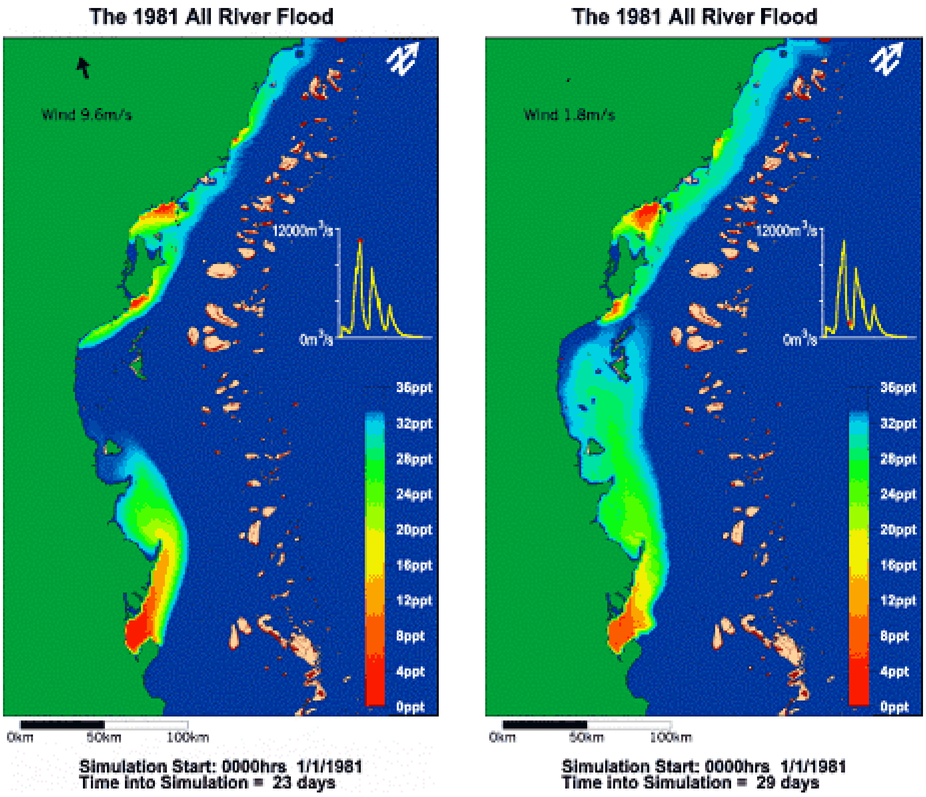


Figure 6. The first flood event which occurred during the 1981 wet season.

Figure 7 shows that the second peak in the flood occurred during northeast winds. On Day 37, Upstart Bay was almost completely freshwater at the surface and the winds had pushed plume waters into the bay to the south of the mouth of the Burdekin River. Plume waters from the Herbert River were pushed southward and mixed with plume waters from the previous Burdekin river flood. The Tully River was experiencing a small flood and plume water advected into the top of Hinchinbrook Island. Note that the plume waters to the north from the previous peak had mixed with continental shelf water and were diluted further. The second flood event subsided after 10 days and a wind change from the south-east pushed the plume waters northward again. The plume waters from this discharge event eventually hit the mid shelf reefs between Day 51-55 with salinity levels down from 35 ppt to 33 ppt. The modelled salinity can be used to determine the degree of mixing and dilution the runoff has undergone, thus the water impacting on the mid-shelf reefs at this time contained approximately 5% freshwater from the runoff of the Burdekin River. Hence the runoff had undergone a 20:1 dilution with ambient seawater by the time it had reached the mid-shelf reefs. Examination of the model results reveals that the runoff water took about 18-22 days to reach these mid-shelf reefs after leaving the river mouth. Therefore the model simulations also made it possible to scientifically estimate dilutions and time frames for transfers of sediment, nutrient and contaminants from land runoff to ecosystems such as mid-shelf reefs.

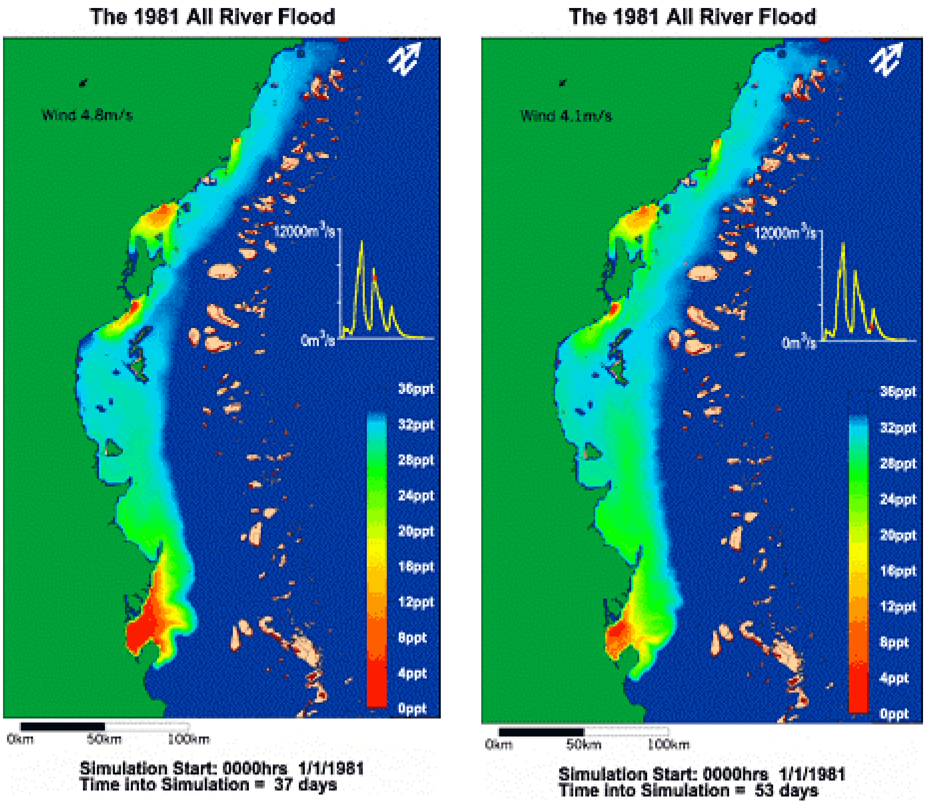


Figure 7. The second flood event which occurred during the 1981 wet season.

The third peak in discharge occurred on Day 55 after Cyclone Freda passed by offshore heading southward (Puotinen *et al.*, 1997). This passage resulted in strong SE winds that peaked on Day 57 (Figure 8). Figure 9 shows winds that exceeded 30 knots and were sufficient to vertically mix the plumes through the water column to depths exceeding 30 m. The wind also pushed the plumes shoreward with some offshore edges retreating 20-40 km under these conditions. This produced significant cross-shelf density gradients that resulted in significant cross-shelf transport of the plume once the winds eased. This cross-shelf transport of the plume eventually hit the mid-shelf reefs on Day 69 with salinities falling to 32-33 ppt at some reefs.

Finally, given that the model of King *et al.* (1998) can reproduce patchiness in the plume, figure 10 shows a comparison between modelled and measured salinity distributions within the GBR. The left insert in figure 10 shows the model predicted surface salinity on 27 January 1981 from discharges from the Burdekin, Herbert, Tully and Johnstone Rivers. The right insert shows the Wolanski and van Senden (1983) distributions of measured surface salinities collected from 26 and 27 January 1981. These measured distributions include the direct rainfall and runoff from other smaller rivers within the region including the Haughton, Ross and Barron Rivers, which are not included in the model predictions. It can be seen from figure 4 that the model predicted river plume positions account for many of the features seen in the measured salinity distributions of Wolanski and van Senden (1983).

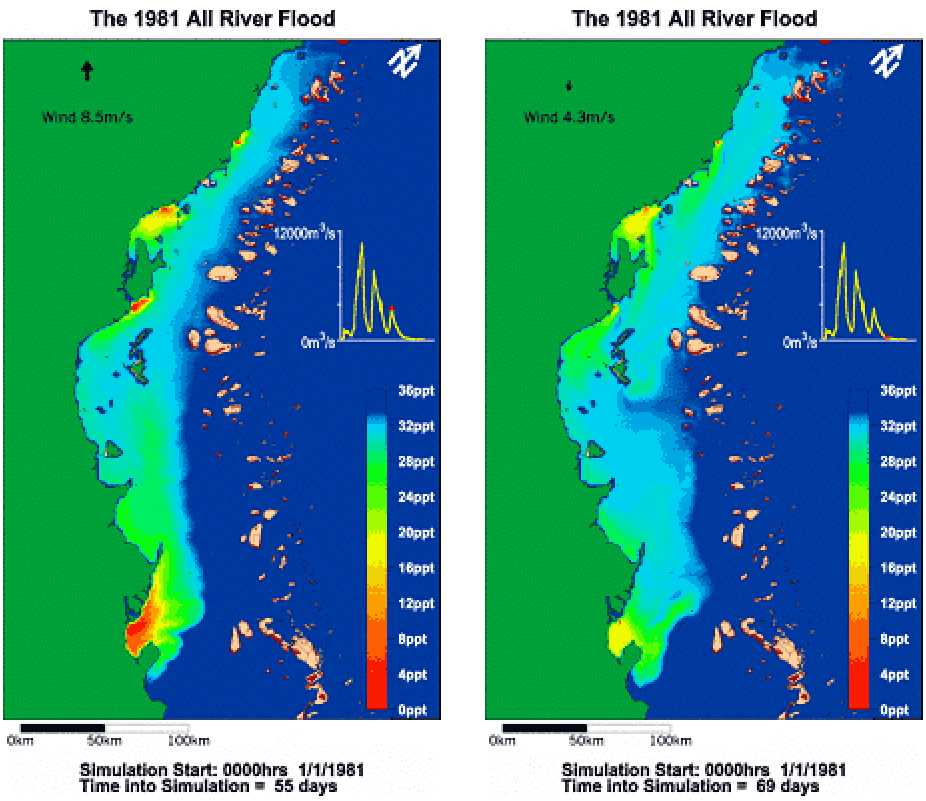


Figure 8. Shows the third flood event which occurred during the 1981 wet season.

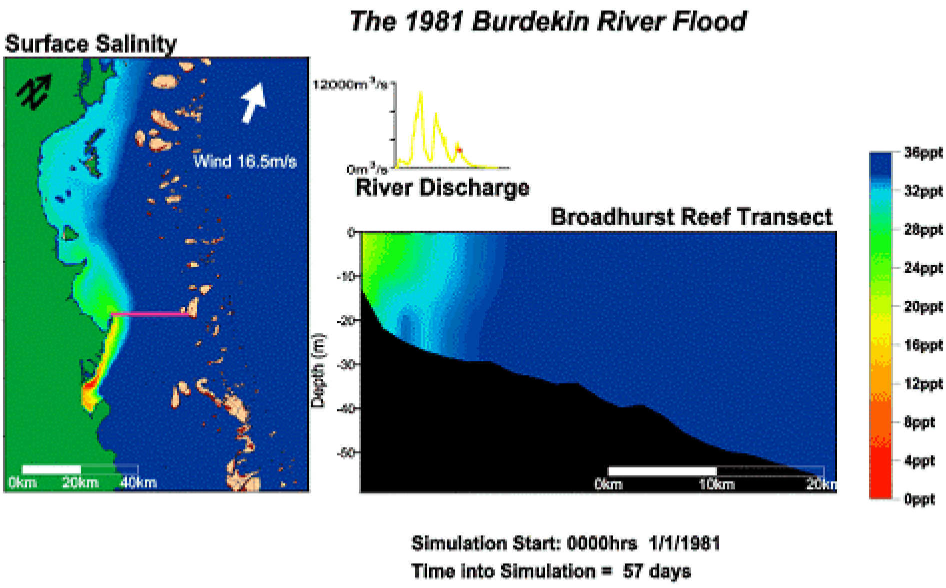


Figure 9. The surface salinity distribution and vertical salinity profile map under the influence of a stong SE wind which pushes the Burdekin plume water towards the coast creating strong vertical salinity gradients across the shelf.

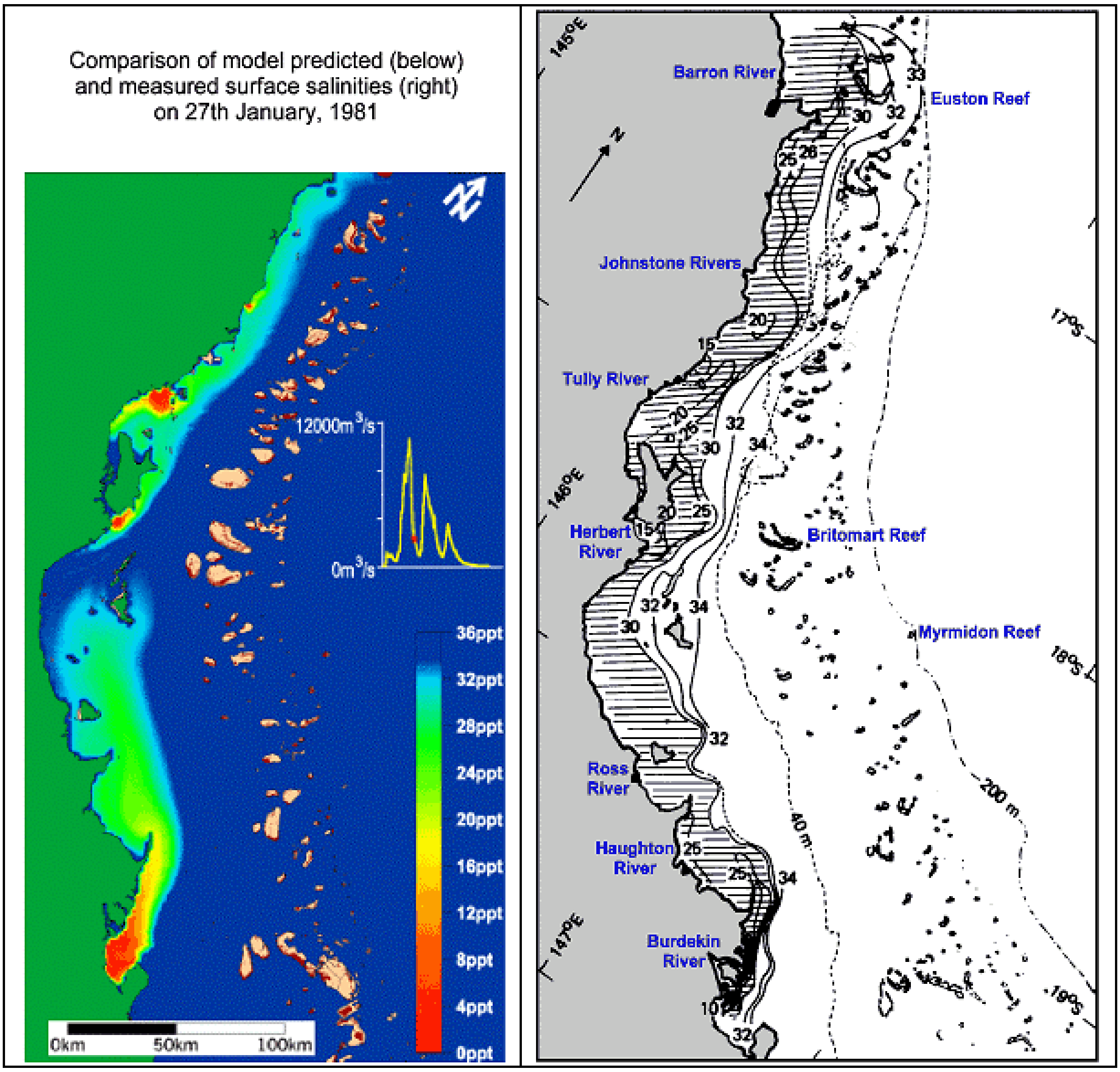


Figure 10. Left insert shows the model predicted surface salinity on 27 January 1981 from discharges from the Burdekin, Herbert, Tully and Johnstone rivers. Right insert shows the Wolanski and van Senden (1983) distributions of measured surface salinities from 26 and 27 January 1981.

Minimum Salinity Analysis

The minimum salinity predicted at each grid cell of the model was extracted for each wet season to examine the concentration extremes and extent of impacts possible from river plumes over many years. Since direct rainfall inputs were not modelled, salinity fluctuations in this model reflected the presence only of freshwater runoff from one or more of the rivers. Thus modelled salinities were direct measures of the runoff dilutions with ambient coastal waters in time and space. Minimum salinity distributions also map the minimum dilutions that substances carried within the runoff will be subjected to (see Table 3). For example, if a region in the model experiences a minimum salinity of 33 ppt when normally the ambient levels are 35 ppt, then that region was exposed to water with a 6% mix of freshwater runoff. Alternatively, Table 3 shows for water containing 33 ppt salinity is obtained when runoff is diluted 1 part runoff with 15.67 parts seawater within the model to lower the salinity 2 ppt from ambient levels (35ppt).

Two examples of the model predicted minimum salinity maps for the 1981 flood event are shown in Figure 11. Figure 11 shows a summary of the flood event from the distributions of the minimum surface salinity predicted by the model. Figure 10 also shows a comparison of the effect of coastal salinities due to the Burdekin River alone and all the rivers. This comparison demonstrates that in 1981, that only Burdekin River water reached the mid-shelf reefs offshore of Magnetic Island (Keeper, Lodestone and John Brewer). Further, Burdekin River water also reached Britomart Reef off Hinchinbrook Island, but was predicted to be more severe when the effects of the Herbert River were included into the model's calculations.

Table 3. Table shows the amount of freshwater runoff and coastal saltwater present in the model predicted salinity distributions and what dilution factor with pure seawater each salinity represents.

Salinity ppt	Freshwater %	Saltwater %	Runoff Dilution Factor
0	100%	0%	0.00
10	71%	29%	0.41
20	43%	57%	1.33
24	31%	69%	2.23
28	20%	80%	4.00
30	14%	86%	6.14
31	11%	89%	8.09
32	9%	91%	10.11
33	6%	94%	15.67
34	3%	97%	32.33
35	0%	100%	No runoff present

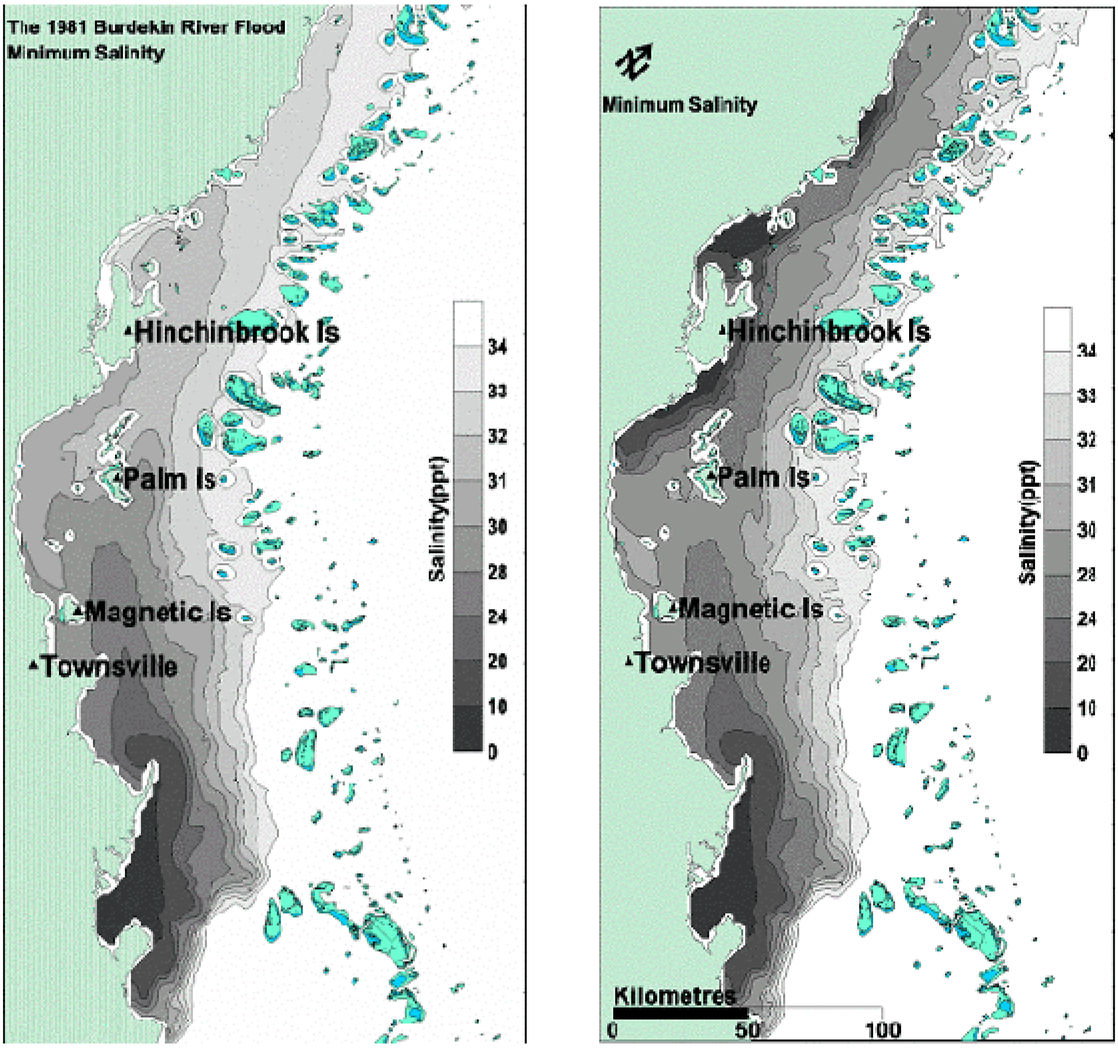
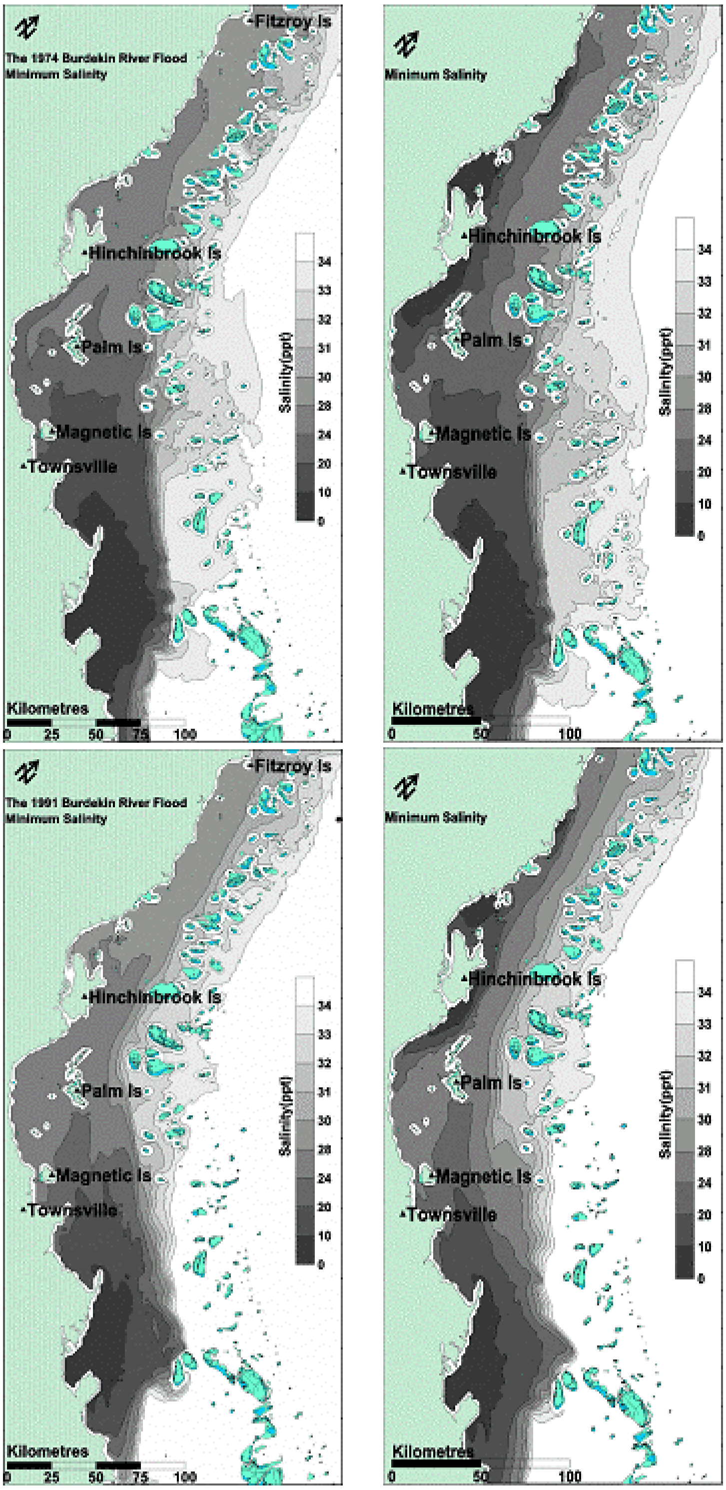


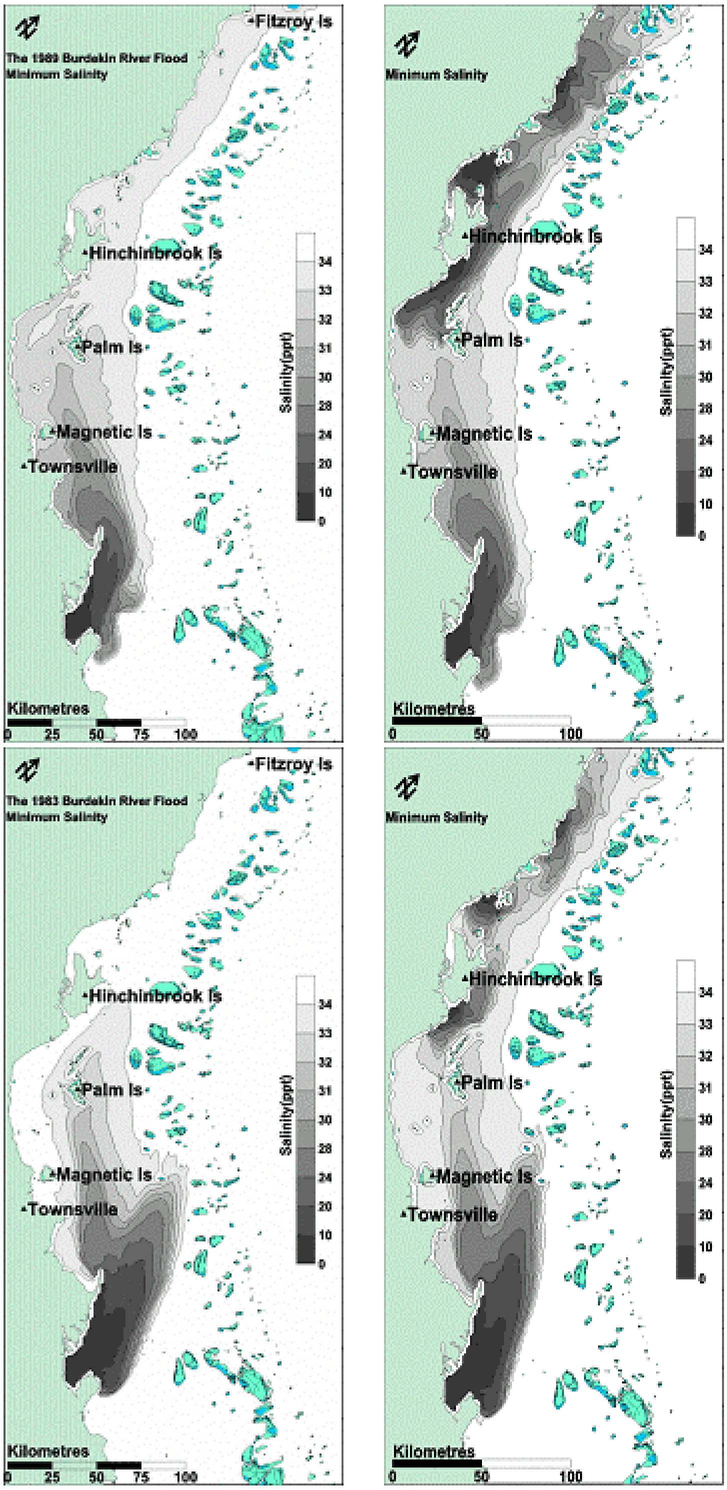
Figure 11. Summary distributions of the minimum surface salinity predicted for each grid cell for 1981 flood events for: (left) discharge from the Burdekin River alone and (right) the discharge effects of all the major rivers.

Minimum Salinity Plots

Modelled examples of minimum salinities modelled from a number of different years are shown in Figure 12. From figure 12 it is possible to compare the spatial variability in plume dynamics and compare the effect of coastal salinities due to the Burdekin River alone and all the rivers. For example, the significant discharge of 1981 ensured that plume waters traveled northward due to Coriolis Effects as the river head pushes its way downstream into coastal waters. The discharge volumes of 1989, 1983, 1997 and 1971 were typical of more common discharge events, calculated to occur once every 2 or 3 years (see Table 1). These years all show the characteristic extensive northward movement of the plume in inshore waters. However, the far-field and offshore extent of the plume varies, since it is significantly influenced by the wind patterns that occurred at each time. Indeed, the influence and timing of wind events enabled more runoff to be delivered to inshore reefs in years like 1983 and 1977 than larger floods like 1981 (Figure 12).

Finally, Figure 12 also shows the distribution of Burdekin Catchment run-off for the driest year of recent times (1992). The plume again flowed northward after entering coastal waters, demonstrating the Burdekin Runoff can influence up to 100 km of inshore waters even under these very low flow conditions.




Fitzroy Is
Minimum Salinity
Hinchinbrook Is
Palm Is
Magnetic Is
Townsville
Salinity(ppt)
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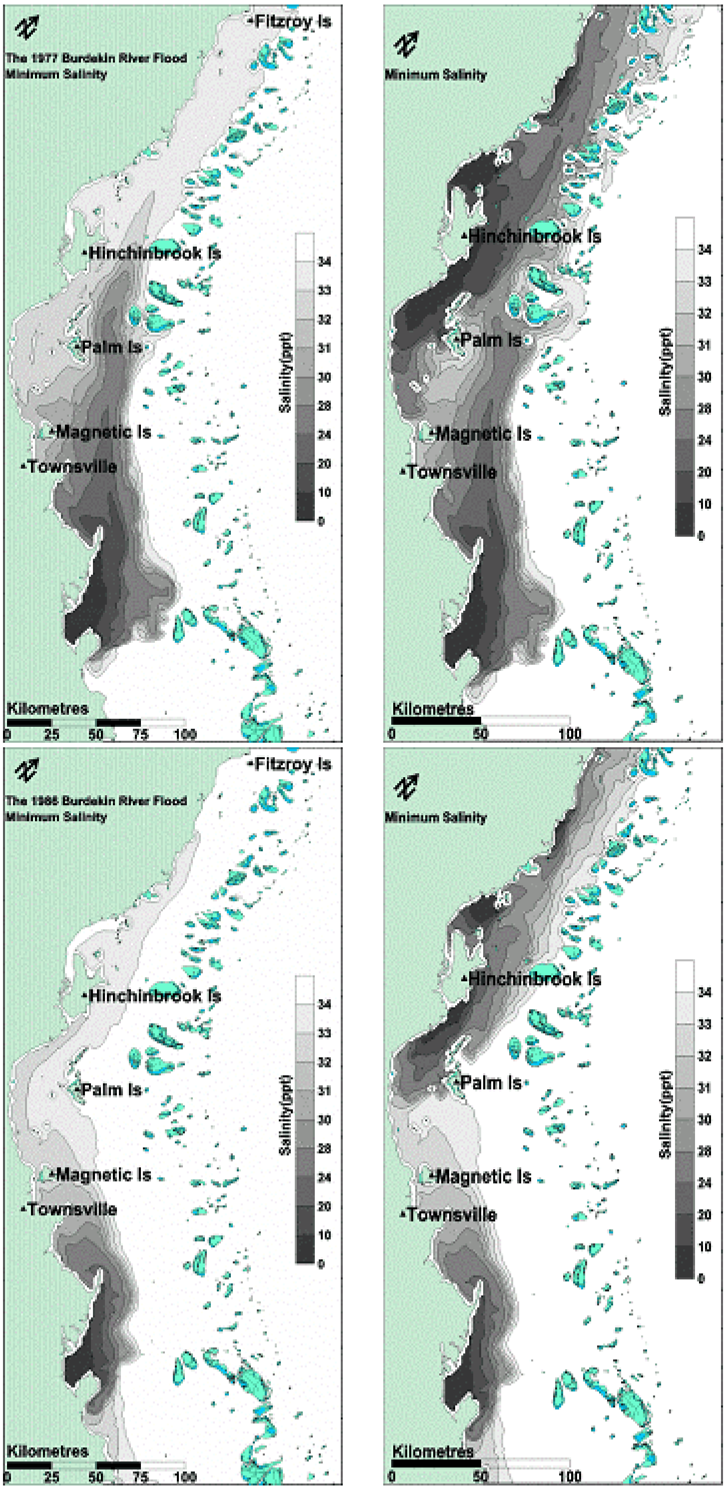
33
32
31
30
28
24
20
10
0
Kilometres
0
25
50
75
100


Fitzroy Is
The 1977 Burdekin River Flood
Minimum Salinity
Hinchinbrook Is
Palm Is
Magnetic Is
Townsville
Salinity(ppt)
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Kilometres
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Minimum Salinity
Hinchinbrook Is
Palm Is
Magnetic Is
Townsville
Salinity(ppt)
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The 1986 Burdekin River Flood
Minimum Salinity
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Magnetic Is
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Salinity(ppt)
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Minimum Salinity
Hinchinbrook Is
Palm Is
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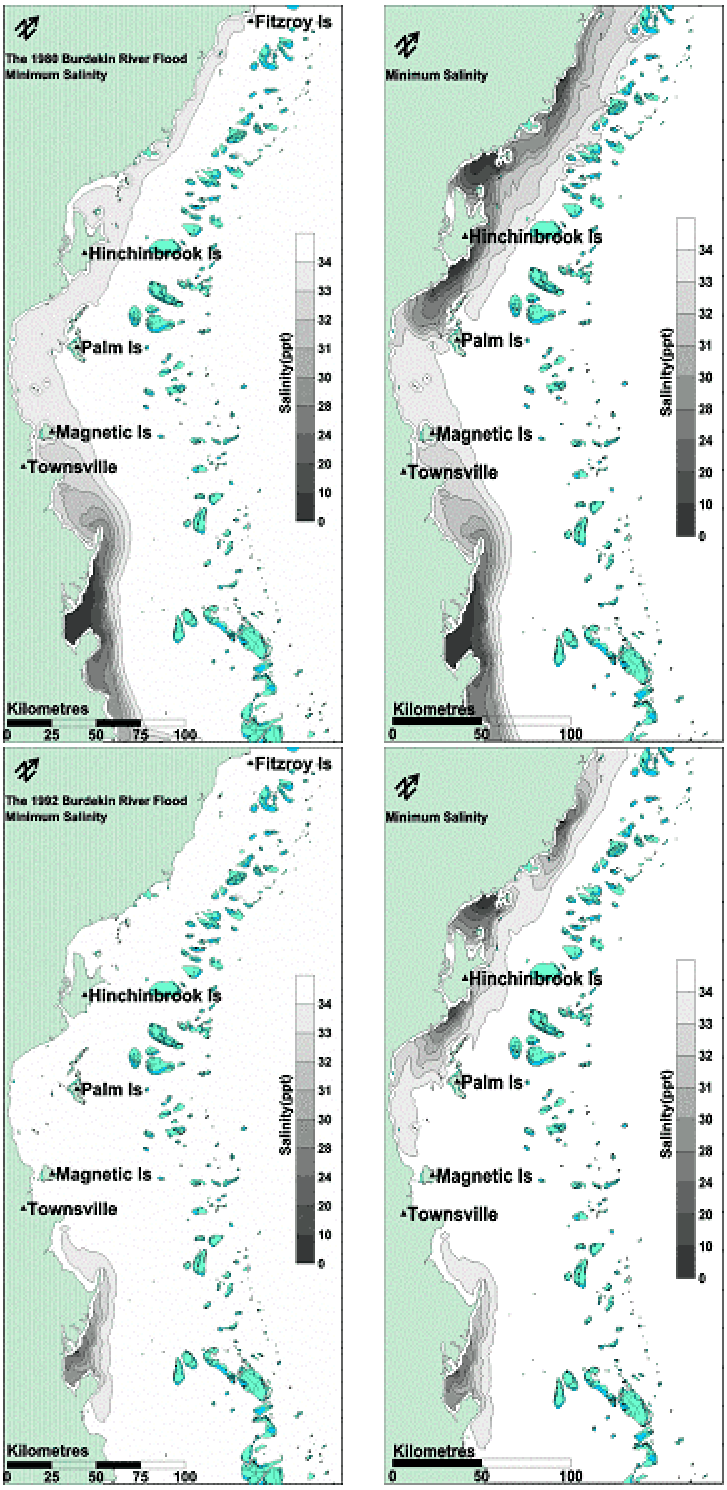


Figure 12. Summary distributions of the minimum surface salinity predicted for each grid cell for 1974, 1991, 1989, 1983, 1977, 1986, 1980 and 1992 flood events for: (left) the discharge from the Burdekin River alone and (right) the discharge effects of all the major rivers.

Exposure Times

Another useful way to take advantage of the model's temporal and spatial resolution was to analyse the modelled salinity predictions and examine the number of times throughout any wet-season that any region was exposed to any low salinity events. This is also known as Exceedence Analysis and maps regions which exceed a given threshold for a threshold duration in time.

Since runoff induces lower salinity events in the model, it was possible to convert salinity levels into concentrations of freshwater runoff as detailed in Table 3. Thus a fresh water exceedance map gives locations which experience lower salinity events while the number of exceedences measured the exposure times that each location was subjected too. Figure 13 shows two Exceedence Maps for the 1981 wet-season. Figure 13 (left) shows the regions subjected to salinity levels of 34 ppt or less for a 120 hour period (5 days). Note, that regions which experienced salinity levels of 34 ppt or lower in the model were regions which endured concentrations of runoff at 3% or greater (from Table 3). In comparison, Figure 13 (right) shows the regions subjected to salinity levels of 31 ppt or less for a 120-hour period (5 days). As expected, for any given wet-season, more area is at risk from events such as 34 ppt than events such as 31 ppt. The number of exceedences is the number of times an event lasting 5 days occurred. For example, for determining impacts of 5-day durations in the 1981 flood event, 36 such 5-day periods existed. A count of six exceedences then, indicates regions that were exposed to 5-day impacts of six occasions. These occasions can be discrete or consecutive.

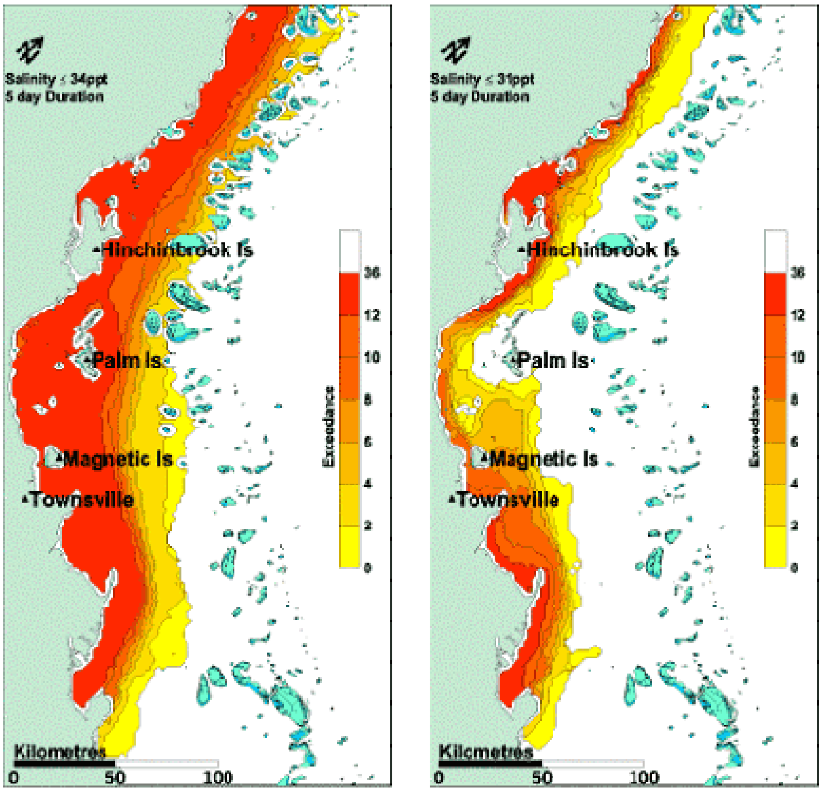


Figure 13. Impact Assessment Maps of the 1981 wet-season. Left insert shows the regions subjected to salinity levels of 34 ppt or less for at least 120 hours (5 days) in 1981. Right insert shows the regions subjected to salinity levels of 31 ppt or less for at least 120 hours during 1981.

Figure 13 demonstrates the spatial variability from impacts from the river plumes. During 1981, the model predicted that all coastal waters and some mid-shelf reefs would be subjected to lower salinity water (34 ppt or less) for at least one 5 day period. The regions which experienced exposure to runoff at higher concentrations, causing salinities to fall to 31 ppt or more.

Simulating the 1974 Flood Event.

The 1974 simulation depicts the biggest flood of the Burdekin River since 1920 when gauging of the river commenced. Table 1 and 2 shows that this event was an extreme event with a likely return period of about 1 in 80 years, based on the total annual discharge volume. The Herbert, Tully and Johnstone rivers also experienced sustained flooding during this period. The discharge was continuous for a 4-month period between 17 December 1973 until 23 April 1974 (Figure 14). Due to the highly active monsoon activity and the passage of several tropical cyclones over the Burdekin and surrounding Catchment areas, more than 70 billion tonnes of freshwater poured from the Burdekin, Herbert, Tully and Johnstone rivers into the GBR lagoon. The peak discharge exceeded a massive 25,000 tonnes of water per second at times for the Burdekin, which resulted in water < 26 ppt reaching as far out as Lodestone, John Brewer and Keeper Reefs. These low salinity events indicate that Burdekin River water can reach the mid-shelf reefs with a dilution rate as low as 1 part river water to 3 parts coastal waters.

Towards the end of the flood (see Figure 15), all 450 km of inshore waters from Abbot Point in the south to Cairns in the north and through the inter reef waters of the Central Great Barrier Reef were exposed to waters drained from the Burdekin, Herbert, Tully and Johnstone River catchment. The plume at this time was 25 km to 100 km wide.

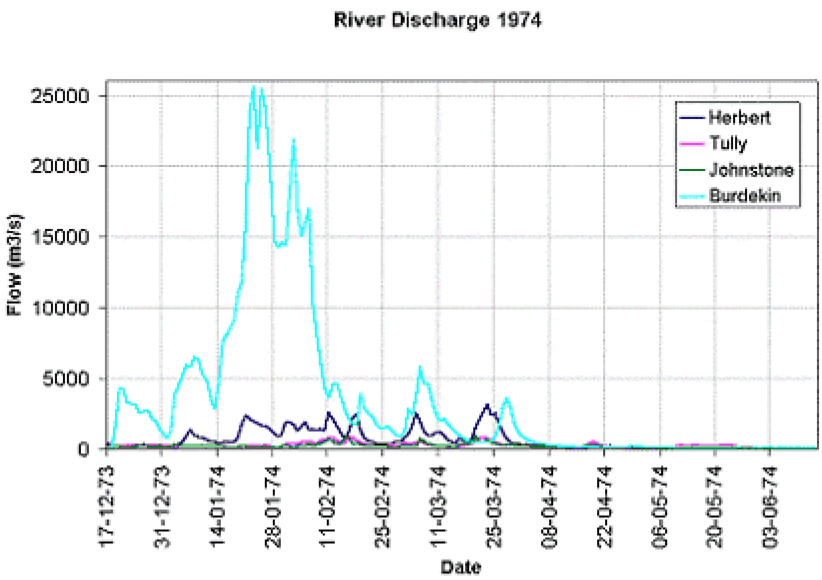


Figure 14. The river discharge for the Burdekin, Herbert, Tully and Johnstone Rivers during the 1973 - 74 wet season.

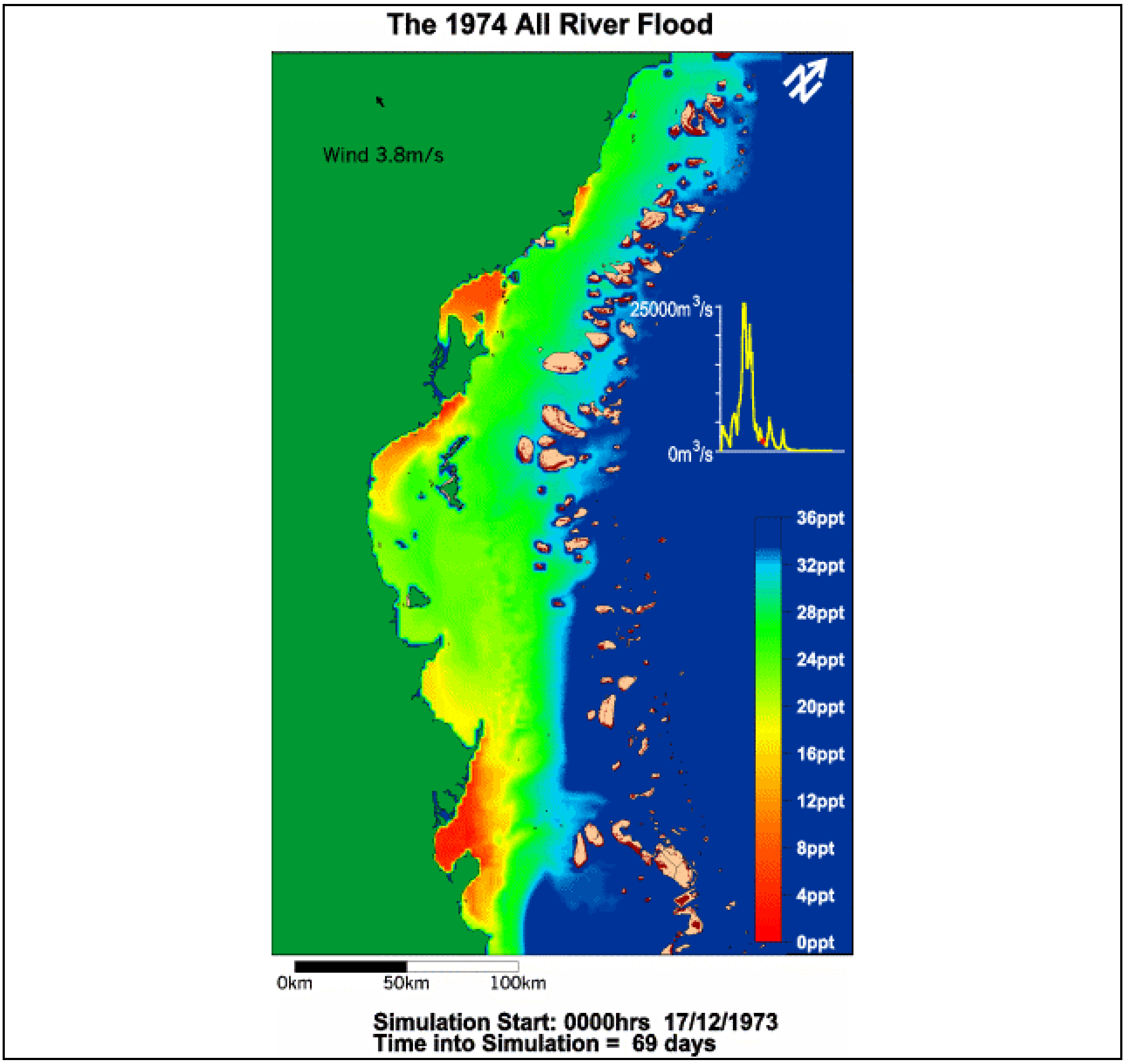


Figure 15. A view of the surface salinity distribution immediately following a sustained discharge period over the 1973 - 1974 wet season. The black arrow in the top left hand corner represents the wind vector at that time. This plume water is predicted to stretch over km along the shelf and at places 100 km offshore.

Simulating the 1991 Flood Event.

The 1991 simulation covers the period from 21 December 1990 until 8 April 1991 and included the discharge from the massive amount of rainfall dumped during the passage of Cyclone Joy (Puotinen *et al.*, 1997) and then due to sustained monsoon activity over the Burdekin and surrounding Catchment areas. The total discharge from this flood was the second highest on record (since 1920) and was about 50 billion tonnes of freshwater. The monsoon activity kept the Burdekin, Herbert and to a lesser extent the Tully and Johnstone rivers discharging for four months with peak discharge rates exceeding a massive 20,000 tonnes/sec for the Burdekin on two occasions and 8000 tonnes/sec for the Herbert river.

The first of these peak discharges for the Burdekin pushed plume water (< 30 ppt) as far offshore as Old and Stanley Reefs (Figure 17). At the time of the second peak discharge, a steady Southeast wind change occurred and pushed the plume waters northwards, filling Bowling Green Bay, Cleveland Bay and Halifax Bay with surface waters < 30 ppt reaching to the Palm Island group and mixing with plume water from the Herbert, Tully and Johnstone rivers. The combined plume was eventually pushed all the way along the coast and mid-shelf reefs to Cairns.

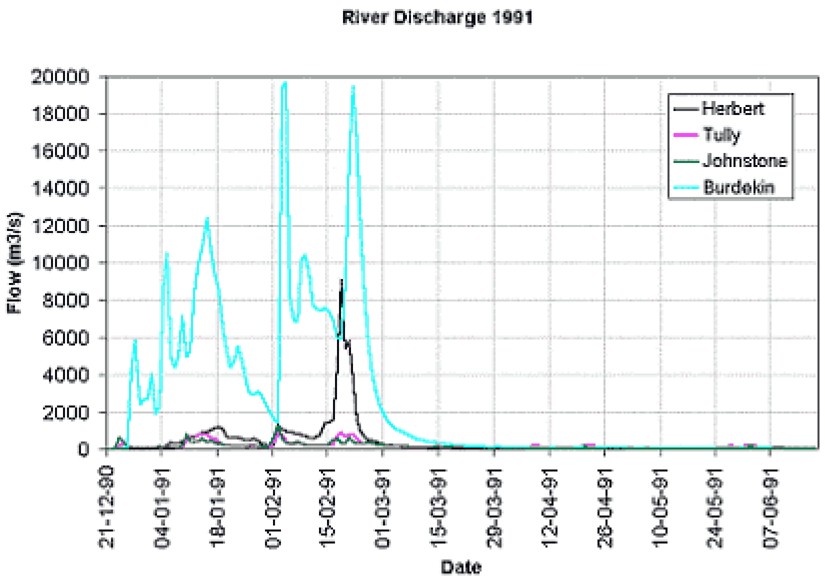


Figure 16. The river discharge for the Burdekin, Herbert, Tully and Johnstone Rivers during the 1990 - 91 wet season.

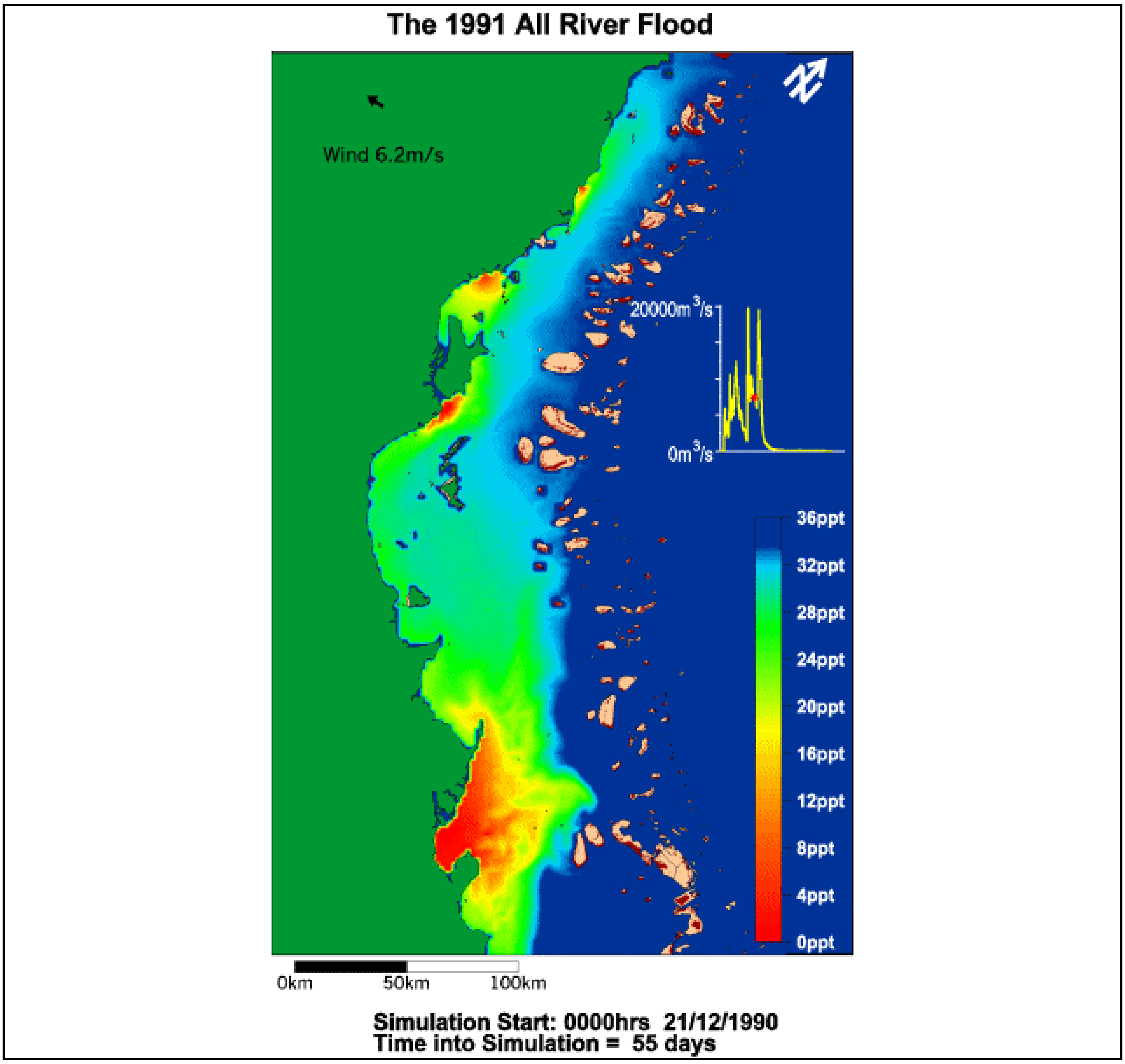


Figure 17. A view of the surface salinity distribution immediately following a sustained discharge period. The insert shows the discharge over the 1990 - 1991 wet season. The black arrow in the top left-hand corner represents the wind vector at that time. This wind pushed plume water into mid-shelf reef waters over significant distances.

Simulating the 1979 Flood Event.

This simulation showed a moderate continuous flood of the rivers from 21 January 1979 until 16 April in 1979. The total discharge from this flood was over 15 billion tonnes of freshwater. Table 1 shows that this volume corresponds to an event that has an expected annual return period of every 4.9 years.

There were two major flood events that occurred during the 1978 - 79 wet season. The first occurred in late January and early February due to interaction between the ridge and monsoonal trough from about 25 until the end of the month which caused flooding in the Burdekin and surrounding catchments. A moderate to strong southeasterly wind forced the Burdekin river plume northward tight against the coast while pushing the river plumes from the Herbert, Tully and Johnstones hard up against the coastline due to the orientation of the coastline in this region, spreading the plumes southward and northward.

The second major flood event occurred from about 12 - 17 March in the Burdekin River with a peak discharge of about 12000 tonnes/sec. Towards the end of the flood, strong 15 to 20 knot southerly winds pushed the plume waters quickly northward with water about 30 ppt reaching to the Palms (Figure 19). The plume eventually reached mid-shelf reefs such as Keeper, Lodestone, John Brewer and Kelso Reef approximately three weeks after leaving the river mouth.

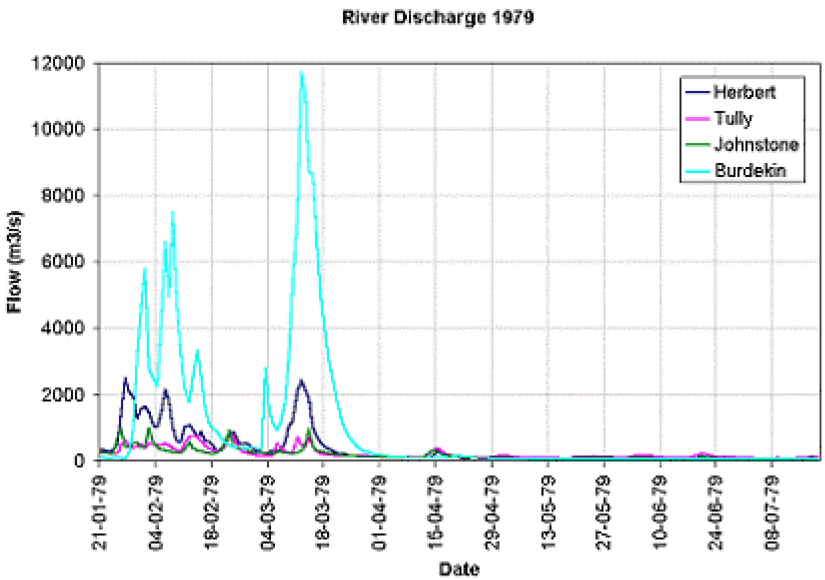


Figure 18. The river discharge for the Burdekin, Herbert, Tully and Johnstone rivers during the 1978 - 79 wet season.

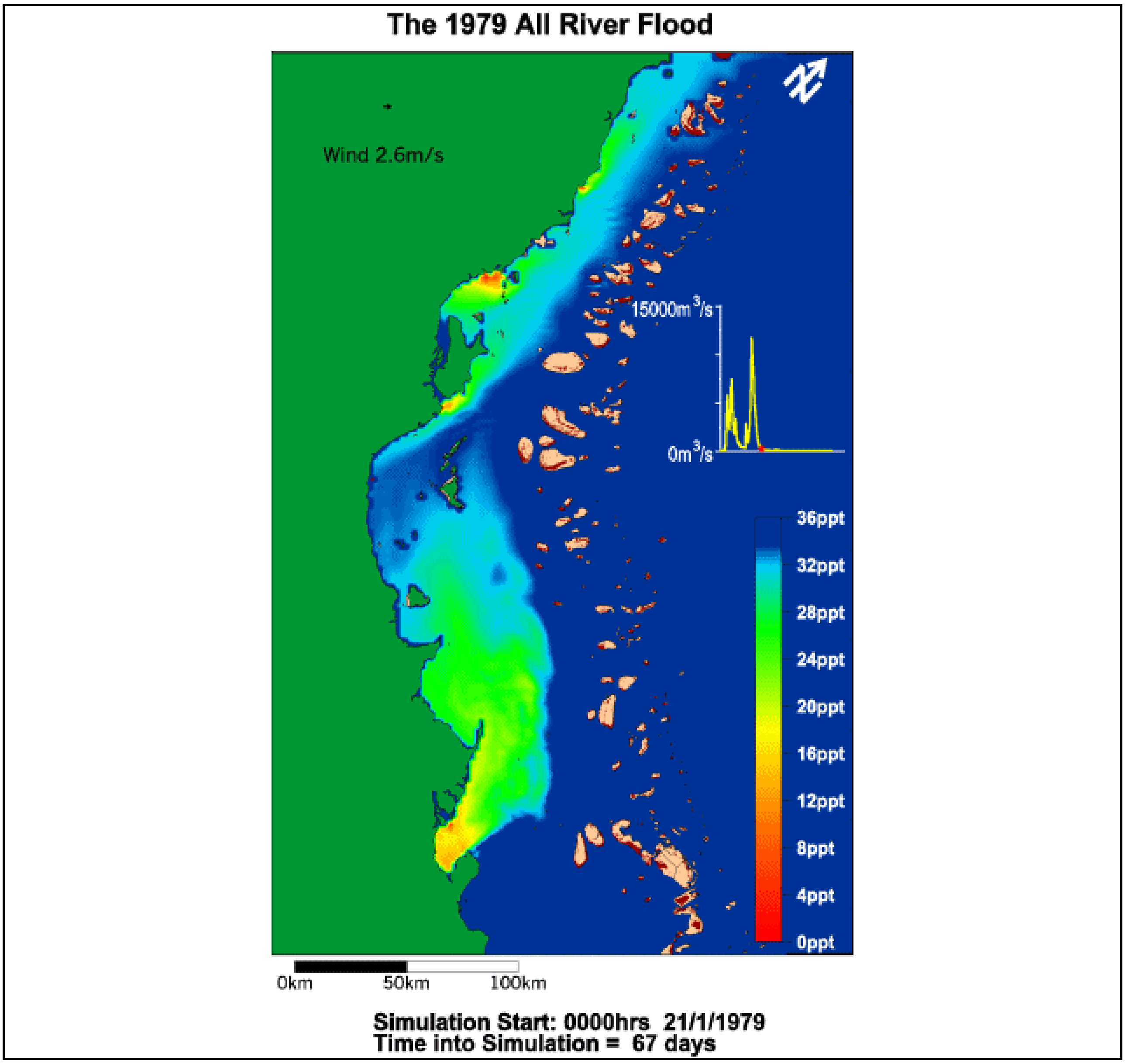


Figure 19. A view of the surface salinity distribution immediately following a sustained discharge period. The insert shows the discharge over the 1978 - 1979 wet season. The black arrow on the compass represents the wind vector at that time. This strong offshore wind pushed plume water into mid-shelf reef waters.

Simulating the 1983 Flood Event.

This simulation covers the period from 25 April, 1983 until 3 August in 1983. The total discharge from this flood was about 10 billion tonnes of freshwater. Table 1 shows that this volume corresponds to an event that has an expected annual return period of every 2.8 years. This event included a massive peak discharge of 10,000 tonnes of water per second on the Burdekin River during 2 May, 1983 due to widespread rain during the last week of April and the first few days of May. At the time of the peak discharge, a strong steady Southwest wind pushed the plume waters northwards with 30 - 32 ppt water reaching the Palms Islands and some mid-shelf reefs (Figure 21).

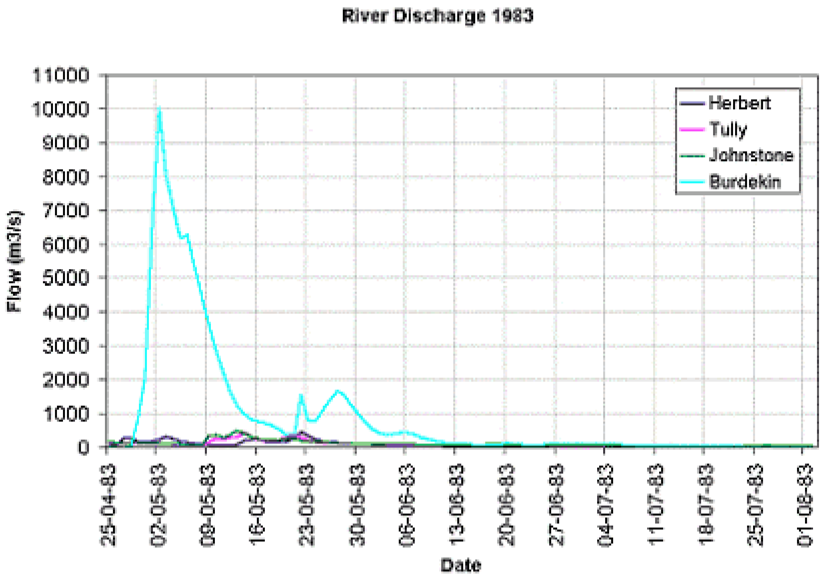


Figure 20. The river discharge for the Burdekin, Herbert, Tully and Johnstone Rivers during the 1983 wet season.

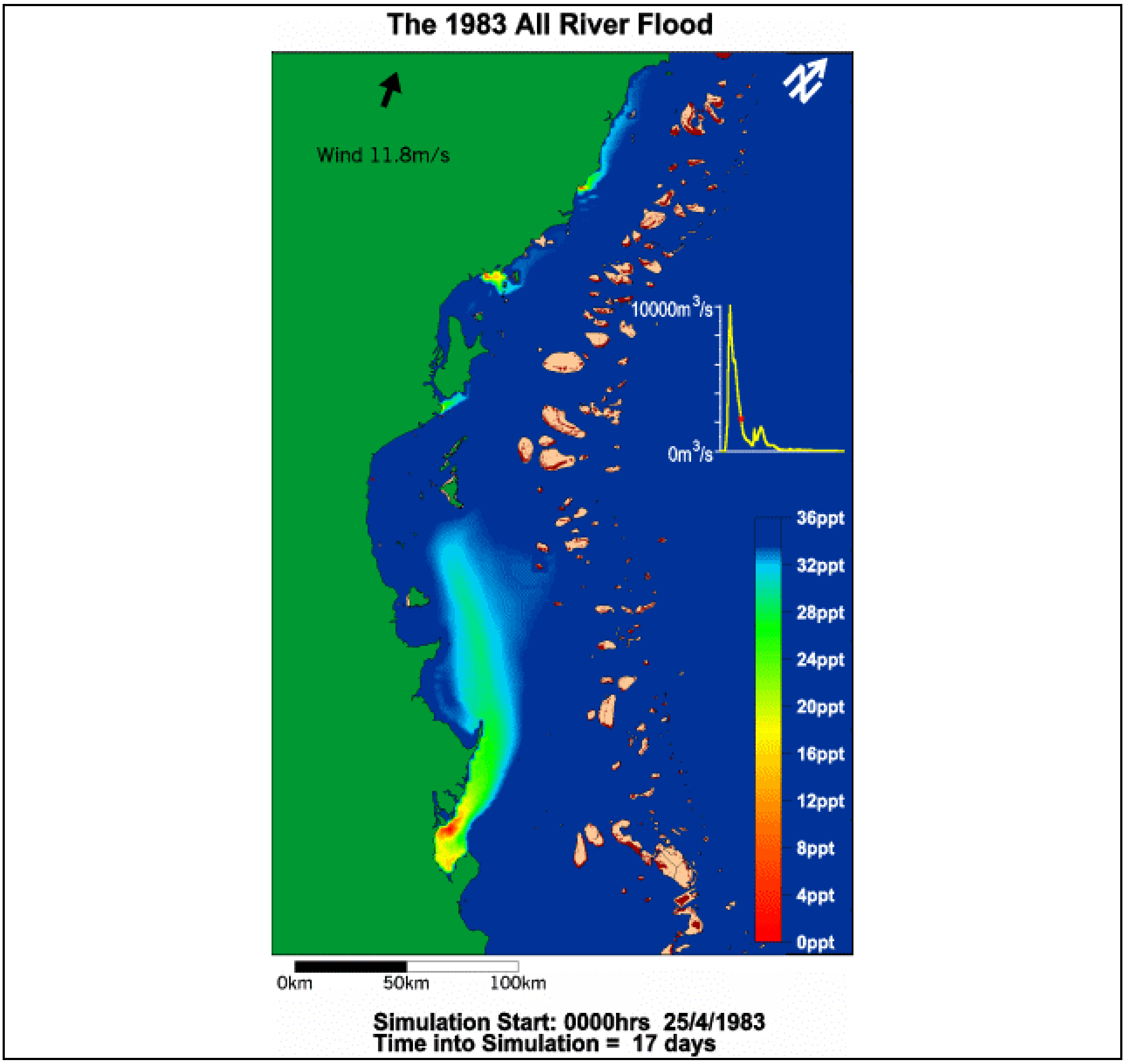


Figure 21. A view of the surface salinity distribution immediately following a sustained discharge period. The insert shows the discharge over the 1982 - 1983 wet season. The black arrow on the compass represents the wind vector at that time. This strong southwest wind pushed plume water northward up the coastline reaching the Palms.

Simulating the 1977 Flood Event.

This simulation covers the period from 22 December 1976 until 20 June 1977. The total discharge from the flood was about 25 billion tonnes of freshwater. The first event occurs late in December 1976 after heavy rainfall on the coastal ranges between St. Lawrence and Cairns, which caused minor flooding in the Burdekin. This event occurred during lighter and variable winds, which created a pooling effect around the river mouth. North to Northeast winds then forced the freshwater plume to drift 50 - 80 km northwards.

The second event occurs in early to mid February with minor stream rises to major flooding occurring in the Herbert, Tully and Johnstone rivers. This was caused by a depression centered over the Barkley Tablelands of the Northern Territory which extended heavy rain in the Lower Carpentaria. Light to moderate variable offshore winds caused river plumes with 30 - 32 ppt water to reach southward to the Palms and northward to Sudbury reef extending out to the mid-shelf reefs in between.

During the second week of March, minor to major flooding occurred in the four coastal rivers due to heavy rainfall with a peak discharge of over 11000 tonnes/sec of water occurring in the Herbert River. The combined effect of the four river plumes and the light variable offshore wind caused river water to reach from the mouth of the Burdekin all the way up to Green Island and Arlington Reef. The plume is 50 - 80 km wide with 30 - 32 ppt water reaching the mid to outer reefs (Figure 23).

During April minor flooding occurred in the Herbert Tully and Johnstone Rivers with 32 ppt water reaching the mid reefs. The Burdekin also experienced minor flooding during May nearing the end of the wet due to depression centred in the south-east of the state. Light southwest winds pushed the river plume northward along the coastline.

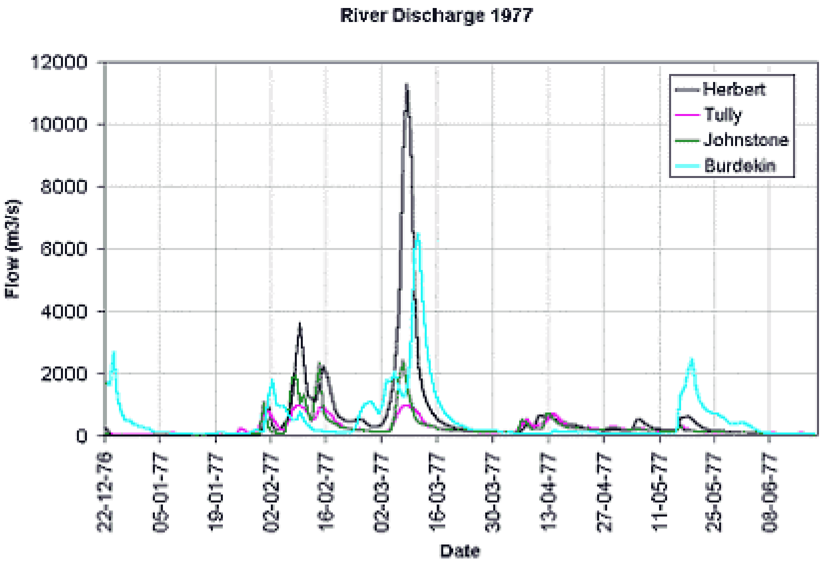


Figure 22. The river discharge for the Burdekin, Herbert, Tully and Johnstone Rivers during the 1976 - 77 wet season.

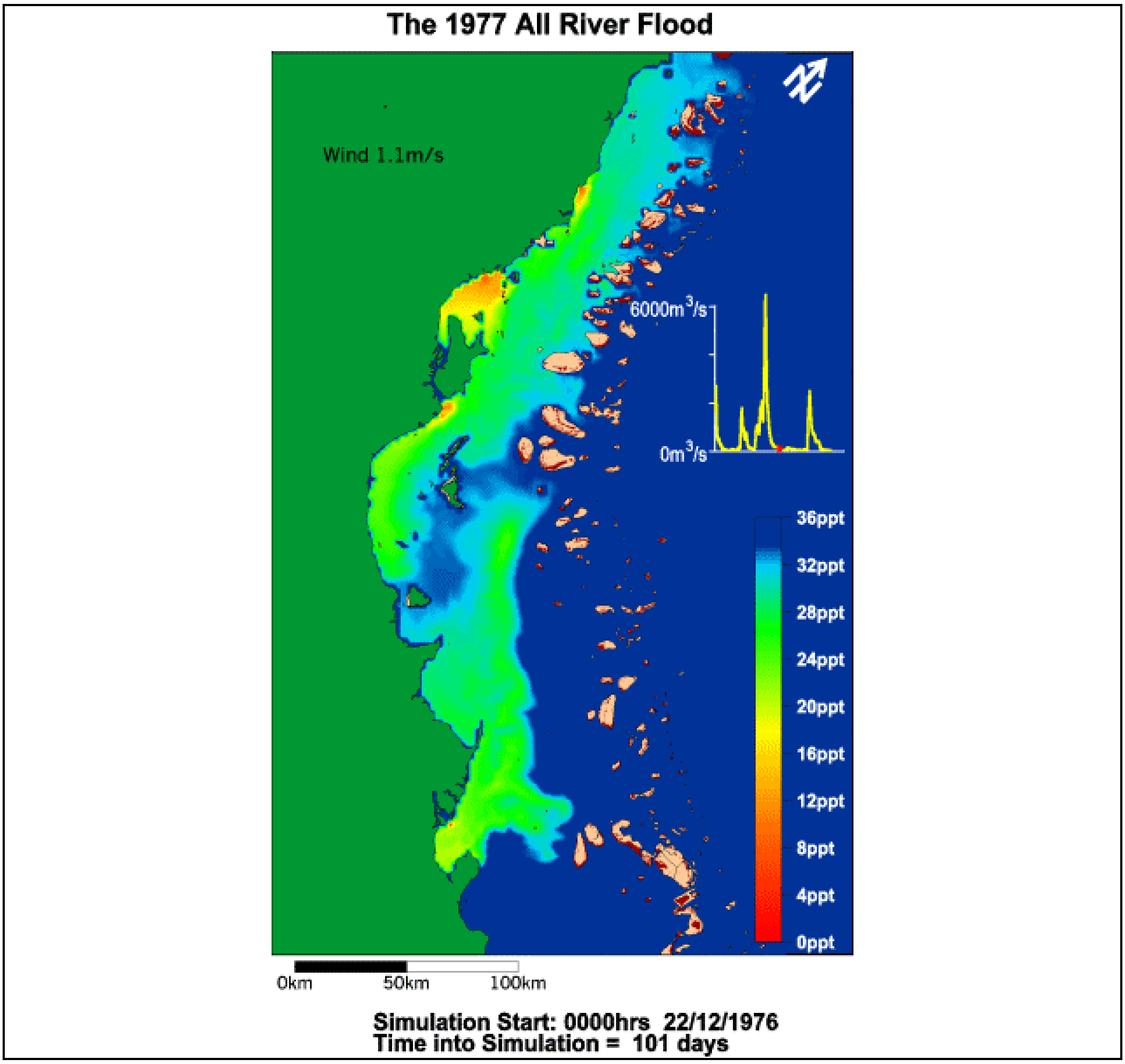


Figure 23. A view of the surface salinity distribution immediately following a sustained discharge period. The insert shows the discharge over the 1976 - 1977 wet season. The black arrow on the compass represents the wind vector at that time. The combined effect of the four rivers caused the river plume to extend from the mouth of the Burdekin to Green Island.

Simulating the 1986 Flood Event.

This simulation covers the period from 22 October 1985 until 20 March 1986. The total discharge from the flood was about 8 billion tonnes of freshwater. A peak discharge of 7000 tonnes of freshwater is the recorded maximum for this period and occurred in the Herbert River on 4 February. Major flooding occurred in the four rivers due widespread heavy rainfall associated with tropical Cyclone Winifred. The week to moderate variable winds caused the associated river plume with 32 ppt water to reach the mid-shelf reefs 2-3 weeks after the event.

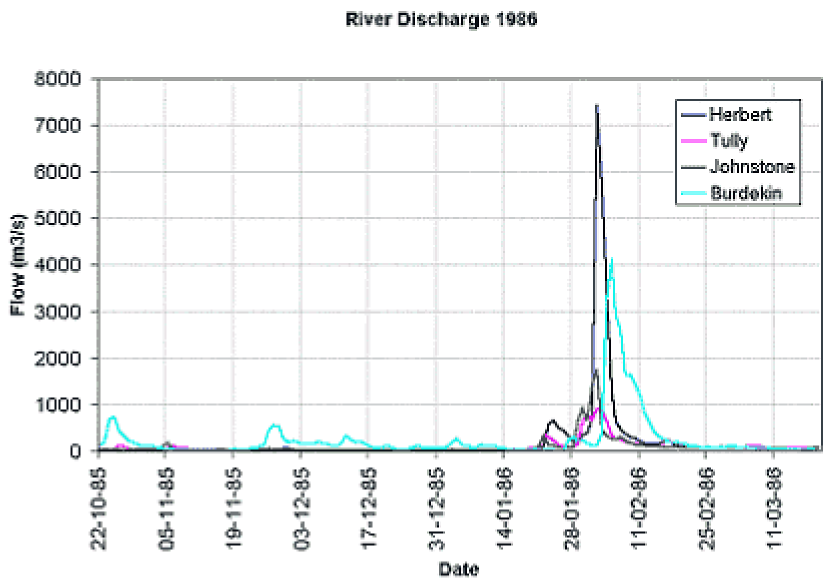


Figure 24. The river discharge for the Burdekin, Herbert, Tully and Johnstone rivers during the 1985 - 86 wet season.

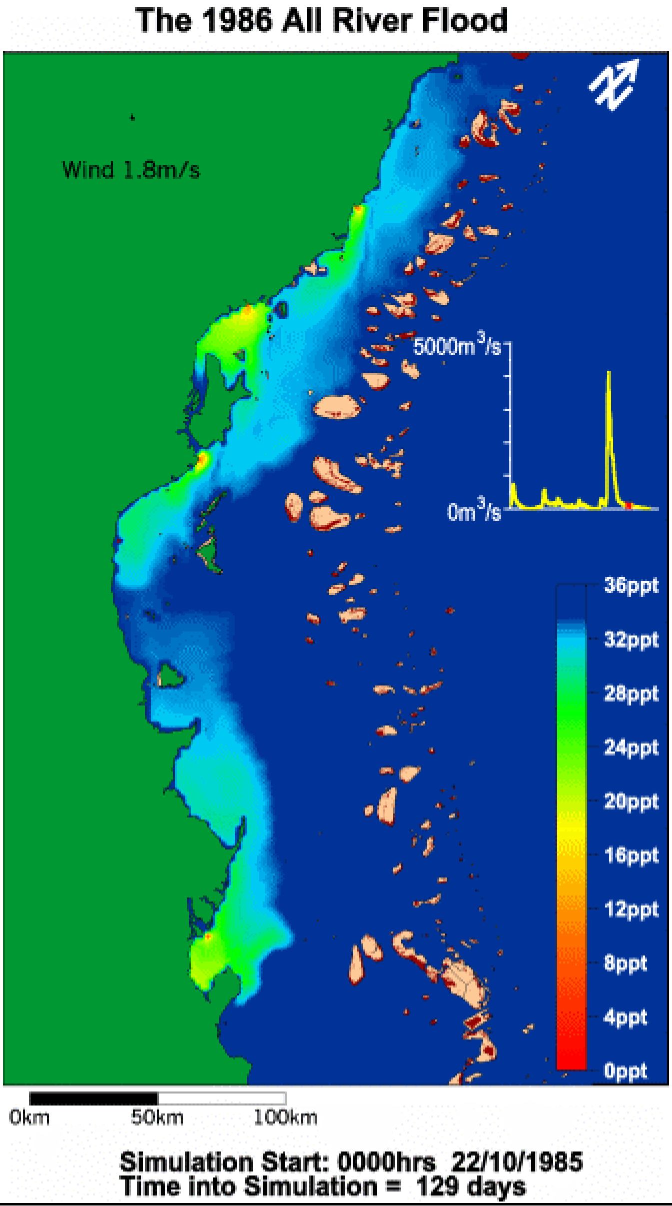


Figure 25. A view of the surface salinity distribution immediately following a sustained discharge period. The insert shows the discharge over the 1985 - 1986 wet season. The black arrow on the compass represents the wind vector at that time. Water consisting of salinity levels 32 ppt and above reached the mid-shelf reefs.

Return Period Estimations of Plume Impacts

Given the natural temporal and spatial variability, which exists in the plume behaviour, the model simulations for all 30 years were compiled to examine the intensity, duration and frequency of different events. The frequency is calculated from the database for each grid cell, by specifying a minimum intensity (in terms of freshwater content) and the minimum duration (in days) or minimum residence time for such an event. So, for example, the event - 31.5 ppt (that is, 10% freshwater), of 24 hour duration refers to an event which the salinity for a cell dropped to 31.5 ppt or below for a continuous period of not less than 24 hours.

Return periods were then calculated from the annual frequency of such events. A count of 1 was assigned to each individual grid cell if a particular year recorded a salinity event occurring at that cell which dropped below an assigned threshold. As this could only be calculated for the years the model was run, the total of these counts for any cell has a maximum of 30 (i.e. at least once every year) and a minimum of 0 (never occurred during the 30 years examined). The actual return period for each cell is thus calculated by the equation:

Return Period = Total Record Length ¸ Count of Annual Occurrence

Therefore a grid cell that records the following counts is assigned a corresponding return period:

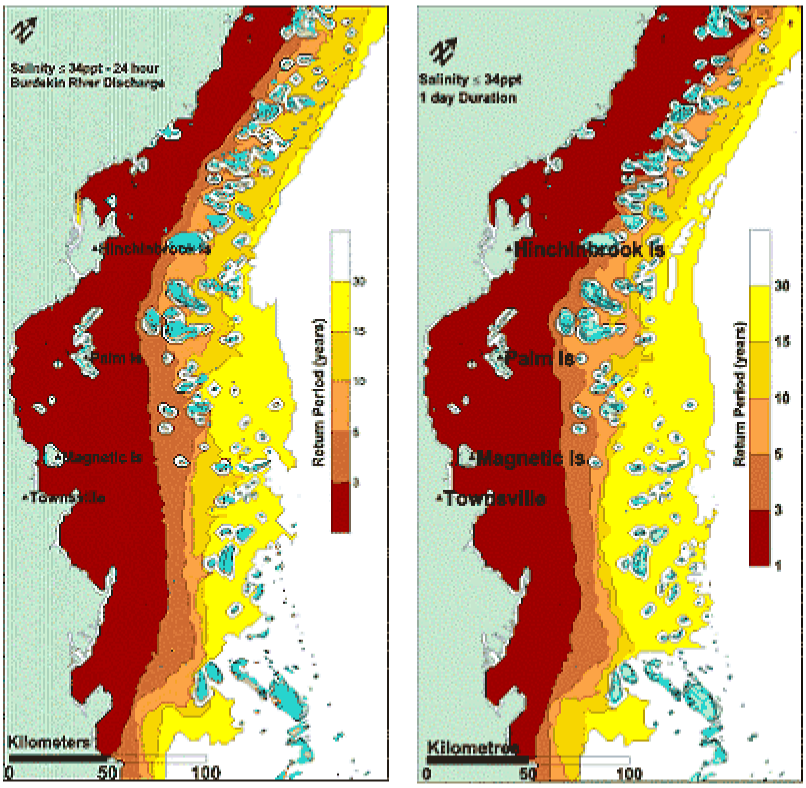
Count	Return Period
2	15
3	10
4	7.5
5	6
6	5
10	3
15	2
30	1

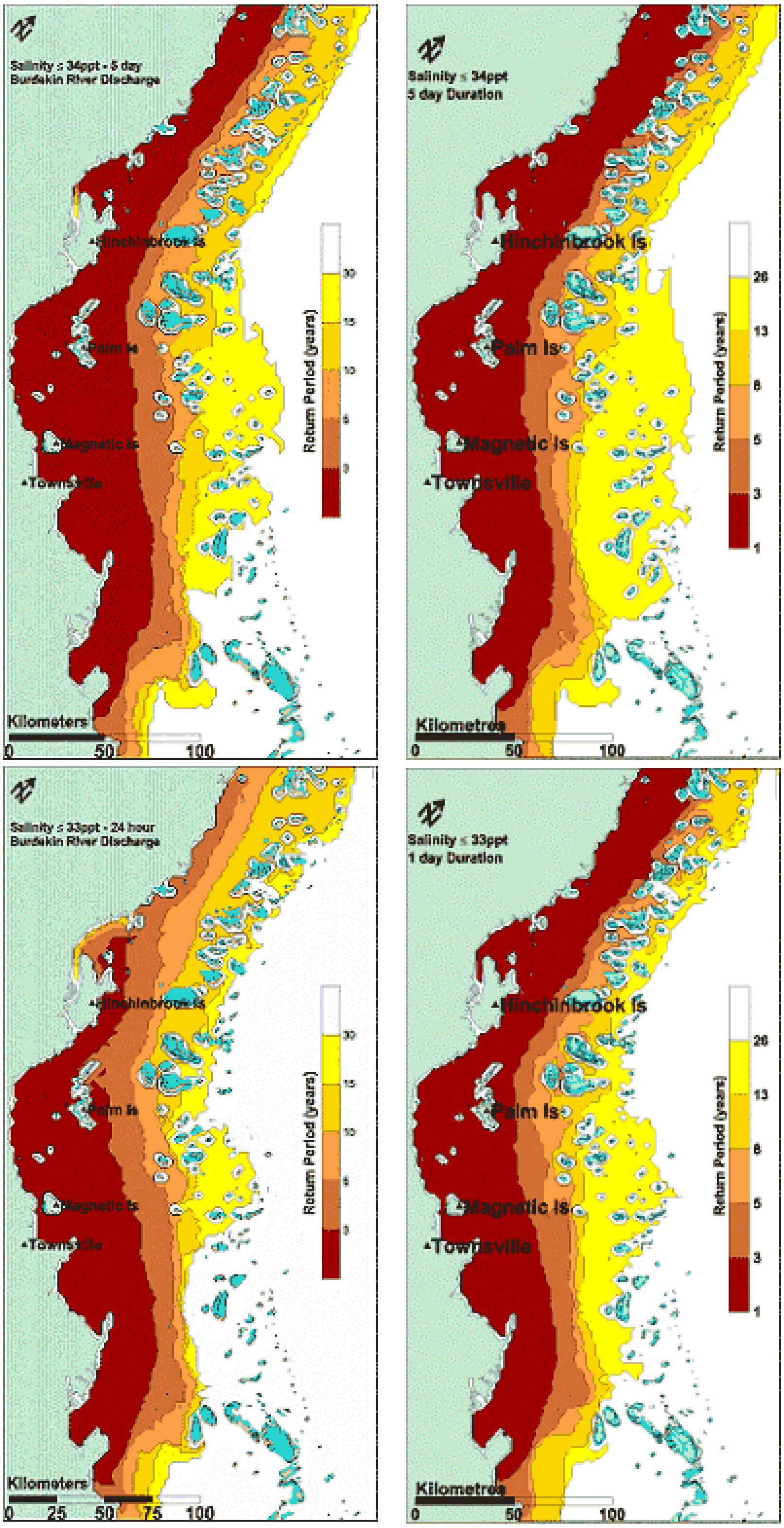
Figure 26 shows examples of the spatial distributions of return periods for plume intensities that exceed typical concentration thresholds and residence times.

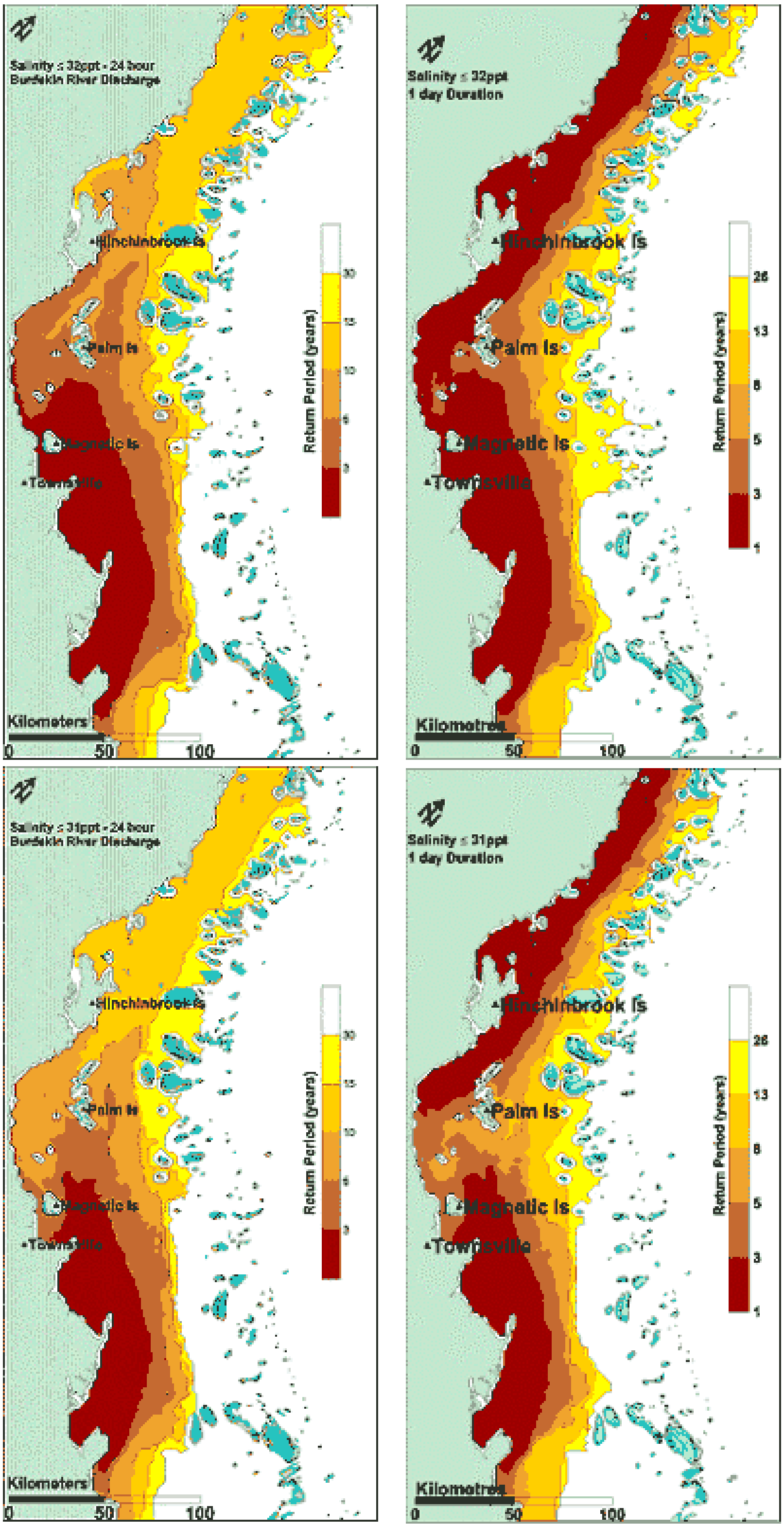
Figure 26 shows the different spatial patterns for surface grid cells which are impacted by the plume at concentrations which exceed a 3% (that is, a 34 ppt low salinity event) mix of Burdekin Runoff (Figure 26, left) and All Rivers Runoff (Figure 26, right) for at least a 1 day and a 5 day duration. Figure 26 demonstrates the notable difference in return periods based on duration. Interestingly enough, Figure 26 suggests that Lodestone Reef is the most likely reef to be impacted by some Burdekin water and hence any soluble or suspended particulate matter still incorporated within the runoff. At Lodestone Reef, an event which exceeds a 3% mix of plume waters, for a minimum of one day would be expected at least once every four years. In comparison, such an event lasting five or more days at Lodestone Reef would be expected once every five years. Figure 26 suggests that this event could be expected at John Brewer, Rib, Keeper, Britomart and Otter Reefs at least once every 5 - 10 years given 1 - 5 day residence time. It is predicted that the fringing reefs of the Palm group will be impacted by such events very frequently at least once every two years.

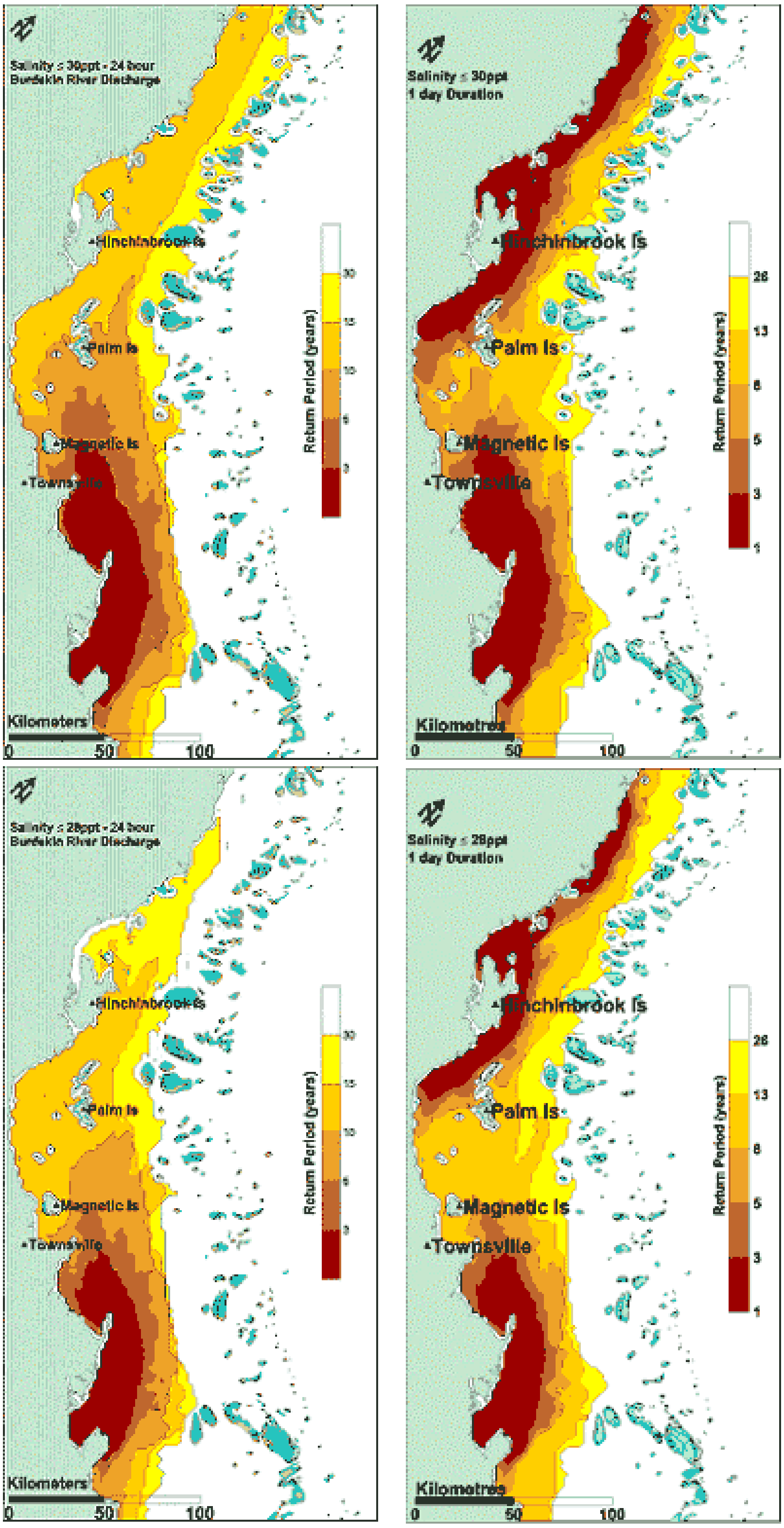
Figure 26 also shows the different spatial patterns for surface grid cells that would be impacted by greater concentrations of Burdekin and surrounding catchment runoff. Figure 26 suggests that the fringing reefs of Magnetic Island and the Palm Group of Islands experience the highest concentrations of All Rivers plume waters where river water content can exceed 15% (a 30 ppt event or less) at frequencies of once every 5 to 10 years. The 30 years of model simulations suggest that inner reefs are unlikely to be subjected to these high concentrations at regular intervals of 10 years or less.

By analysing the 30-year simulation for the frequency of short-term events which exceed a 10% mix of Burdekin and All Rivers plume waters (Figure 26 on the left and right respectively) (32 ppt) suggest that Lodestone Reef will be at most risk, with an expected occurrence of one event in a 10 year period (Figure 26). The fringing reefs of Magnetic Island would be subjected to such events once every 2 or 3 years while the fringing reefs in the Palm Group would expect an impact exceeding these concentrations once eve ry 2 - 5 years.




Salinity ≤ 34ppt - 5 day
Burdekin River Discharge
Hinchinbrook Is
Palm Is
Magnetic Is
Townsville
Return Period (years)
30
15
10
5
3
Kilometers
0
50
100
Salinity ≤ 34ppt
5 day Duration
Hinchinbrook Is
Palm Is
Magnetic Is
Townsville
Return Period (years)
26
13
8
5
3
1
Kilometres
0
50
100
Salinity ≤ 33ppt - 24 hour
Burdekin River Discharge
Hinchinbrook Is
Palm Is
Magnetic Is
Townsville
Return Period (years)
30
15
10
5
3
Kilometers
0
25
50
75
100
Salinity ≤ 33ppt
1 day Duration
Hinchinbrook Is
Palm Is
Magnetic Is
Townsville
Return Period (years)
26
13
8
5
3
1
Kilometres
0
50
100


Salinity ≤ 32ppt - 24 hour
Burdekin River Discharge
Hinchinbrook Is
Palm Is
Magnetic Is
Townsville
Return Period (years)
Kilometers
0
50
100
Salinity ≤ 32ppt
1 day Duration
Hinchinbrook Is
Palm Is
Magnetic Is
Townsville
Return Period (years)
26
13
8
5
3
1
Kilometres
0
50
100
Salinity ≤ 31ppt - 24 hour
Burdekin River Discharge
Hinchinbrook Is
Palm Is
Magnetic Is
Townsville
Return Period (years)
Kilometers
0
50
100
Salinity ≤ 31ppt
1 day Duration
Hinchinbrook Is
Palm Is
Magnetic Is
Townsville
Return Period (years)
26
13
8
5
3
1
Kilometres
0
50
100



Salinity ≤ 30ppt - 24 hour
Burdekin River Discharge
Hinchinbrook Is
Palm Is
Magnetic Is
Townsville
Return Period (years)
Kilometers
0
50
100
Salinity ≤ 30ppt
1 day Duration
Hinchinbrook Is
Palm Is
Magnetic Is
Townsville
Return Period (years)
26
13
8
5
3
1
Kilometres
0
50
100
Salinity ≤ 28ppt - 24 hour
Burdekin River Discharge
Hinchinbrook Is
Palm Is
Magnetic Is
Townsville
Return Period (years)
Kilometers
0
50
100
Salinity ≤ 28ppt
1 day Duration
Hinchinbrook Is
Palm Is
Magnetic Is
Townsville
Return Period (years)
26
13
8
5
3
1
Kilometres
0
50
100

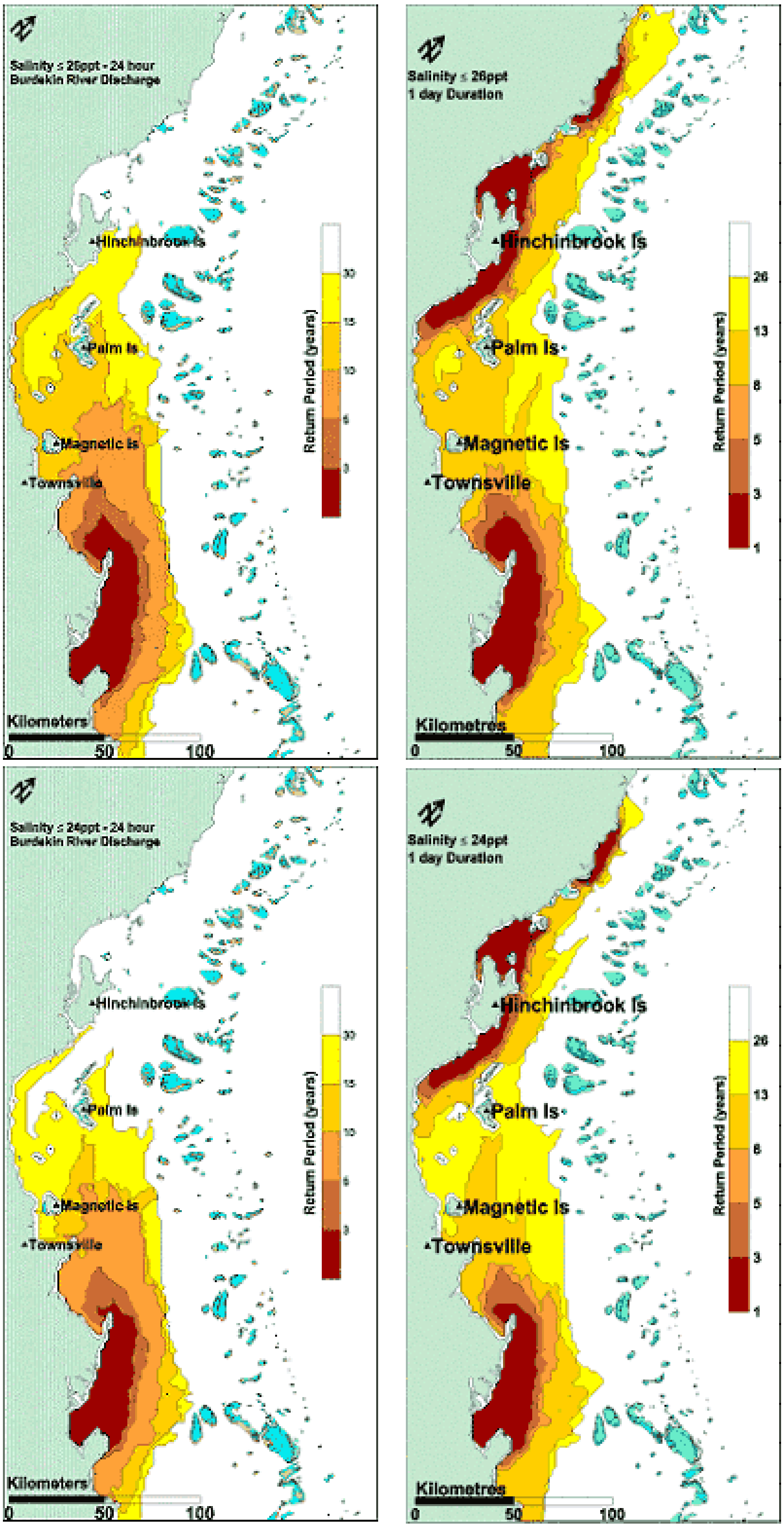


Figure 26. Return Period calculations showing the likelihood of an impact which exceeds a 3%, 7%, 9%, 11%, 14%, 20%, 26%, 31% concentration (Burdekin Runoff, map on left. All Rivers Runoff, map on right) for at least a one day duration.

CONCLUSION

The calibrated and verified 3-dimensional hydrodynamic model MECCA (see Hess 1989) from NOAA, was employed to simulate the Burdekin River in flood from 1966-1995 and the combined effect of the Burdekin, Herbert, Tully and Johnstone Rivers from 1973-1998. The simulations were used to investigate the dynamics of the Burdekin, Herbert, Tully and Johnstone catchment runoff plumes into the waters of the Central Great Barrier Reef (CGBR).

The model domain was represented by a sigma grid and covered the entire shelf of the CGBR from Cairns to Bowen. The grid comprised of over 100,000 computational points (five layers in the vertical, 211 points in the along-shelf direction and 95 across-shelf). Given the huge discharge from the rivers at times, it was necessary to set the 100,000 node 3D model to a 30-second time step for both the external mode and internal mode. Consequently, the simulations for all 30 years took about 100 days of CPU time on a dedicated PIII 500 MHz PC. The simulations required in excess of 10 quadrillion calculations to produce a comprehensive time varying and 3-dimensional spatially varying database of the fate and mixing of plume waters from the Burdekin River and from the combined effects of the plumes from the Burdekin, Herbert, Tully and Johnstone Rivers.

The output from the simulations were stored every six hours creating an extensive database of runoff induced salinities in the CGBR. Animations of the predicted plumes from 1973 to 1998 were also created from the model outputs to detail the dynamics of these plumes. The animations, covering 26 years of floods in the region, demonstrate the events that lead to an intrusion of river plumes into reef waters. Further, the database can be used to examine dilution of rivers plumes with ambient salinity levels (35 ppt, see Wolanski, 1994) as a measure of the concentrations of river water in each of the 20,000 surface grid cells over many years. For example, at 30 ppt low salinity event is given for grid cells containing a 15% mix of freshwater with seawater, while a 34 ppt low salinity event is given for grid cells containing a 3% mix of freshwater. The animations were used to view the plume trajectories, distributions and dilutions.

The simulations showed that the Burdekin River plume regularly stretches over 400 km to the north in coastal waters when examined in isolation. In contrast, the simulations of the Burdekin, Herbert, Tully and Johnstone Rivers showed that collectively, plume waters stretched even further north due to the added discharge reducing far field dilutions of the Burdekin plume.

The model simulations demonstrated that some of the patchiness in the plumes occurred due to daily variability in the wind field and discharge rates. Steering effects from the coastal topography, continental islands and the dense reef matrices further create complex spatial patterns in the plume distribution. For the smaller rivers in this region, such as the Herbert, Tully and Johnstone systems, plume movements are more variable as wind and local topographic effects tend to dominate plume fate due to their lower discharge rates.

The database and simulations of the Burdekin in Flood (1966-1995) and the combined effects of the Burdekin, Herbert, Tully and Johnstone Rivers (1973-1998) revealed the range of possible pathways which would explain the connectivity of land runoff to the coastal zone and the reefs. The database has shown that the catchment runoff begins mixing with coastal water once leaving the river and hence land derived pollutants are continually diluted with time. While the discharge behaviour differs every year, the results show that Burdekin Catchment Runoff annually reaches 100 km northward with dilutions of 1:20 or lower.

The model also predicted that shelf edge reefs in the CGBR were unlikely to be affected by these river plumes, but that the mid-shelf reefs were impacted when an offshore wind prevailed following a flood event. The simulation of the extreme 1974 discharge produced a low salinity event of 26 ppt at the mid-shelf reefs. Hence river waters can reach mid-shelf reefs with a minimum dilution rate of 1 part river water to 3 parts coastal seawater. The simulations also showed that the plume would usually take at least a 2-3 week period, after discharge from the river mouth, to reach the mid-shelf reefs.

Plumes typically reach the bottom in shallow coastal waters (< 10m) although model simulations suggest that strong discharge and wind events will mix plume waters to depths of 30m at times. In deeper waters, under more moderate conditions, plumes tend to be less dense than surrounding offshore waters. This density difference enables the plume to float buoyantly at the surface and drift with the wind, stratifying the water column. The buoyant plume also continues to spread and mix while on the surface, and has been observed to be 10-20 m thick, even through the mid-shelf reef regions

Given the natural temporal and spatial variability that exists in the plume behaviour, the model simulations for all the years examined, were compiled to examine the intensity, duration and frequency of different lower salinity events. Return periods were then calculated for such events over the entire model domain. This analysis reveals that close proximity to the river mouth does not necessarily increase the likelihood of impact. Indeed, the closest reefs to the mouth of the Burdekin River are only 50 km away, yet the most frequently impacted regions from this river (Lodestone Reef, Rib Reef, John Brewer Reef, and Keeper Reef) are over 120 km away. Finally, the return period analysis showed at 2km resolution, which inner shelf reefs and midshelf reefs are most 'at risk' from land runoff and catchment management practices from these river basins when in flood.

From a management perspective, the simulations can identify the fate of the Burdekin River plume in isolation to other freshwater discharges, which cannot be done with field observations. This information should provide useful information on catchment management implications of the Burdekin region and its impact on shelf and Great Barrier Reef waters. This model and the resulting database of Burdekin River plume distributions demonstrate the link between local catchment management practices and their likely impact on the reefs and coastal waters of the CGBR. Similarly the combined effect of the all the rivers plume can be used to gauge the effects of the impact of larger freshwater discharges over a greater area. This information can be compared to field observations and provide useful information on catchment management and provide a picture on the likely impact to reefs and coastal waters. The simulations predicted the range of potential dilutions of river water under a range of discharge and wind regimes. Any dissolved material carried with the river water will also be subjected to the same dilution ratios as the freshwater. The return periods have highlighted the regions that are most likely to be impacted by plume waters and hence have identified suitable locations for establishing any monitoring programs for assessments of land use changes within the Burdekin, Herbert, Tully and Johnstone rivers and their catchment areas.

DISCUSSION

To date, observations and modelling studies on the river plume dynamics in the GBR have showed that plume trajectories are complex and event driven. Given the natural temporal and spatial variability and hence patchiness observed in plume behaviour, a risk assessment and return period analysis from many years of observations or model simulations over decades is required to examine the intensity, duration and frequency of plume impacts in coastal and reef waters of the GBR. This report and King *et al.* (2000) detail such an analysis for the simulations of the Burdekin plume in isolation and the Burdekin, Herbert, Tully and Johnstone Rivers. This database was ultimately analysed to map the return periods of the likely impacts of runoff from four major rivers to nearby reefs in the Central Great Barrier Reef (King *et al.* 2000, McAllister *et al.* 2000). In particular, the return period analysis shows which inner and mid-shelf reefs are most ‘at-risk’ from land runoff and catchment management practices from these river basins when in flood.

While this analysis provides stakeholders with a spatial and temporal risk assessment of river plumes in the Central Section of the Great Barrier Reef, the risk profile imposed by the other catchments and river systems in the Northern and Southern sections of the Great Barrier Reef may differ significantly and remain unexplored.

ACKNOWLEDGEMENTS

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